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(12) United States Patent
Inoue et al.

(10) **Patent No.: US 9,117,961 B2**

(45) **Date of Patent: Aug. 25, 2015**

(54) **NITRIDE-BASED SEMICONDUCTOR LIGHT-EMITTING ELEMENT**

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(73) Assignee: **Panasonic Intellectual Property Management Co., Ltd.**, Osaka (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 32 days.

(21) Appl. No.: **13/778,727**

(22) Filed: **Feb. 27, 2013**

(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation of application No. PCT/JP2012/002385, filed on Apr. 5, 2012.

(30) **Foreign Application Priority Data**

Jul. 14, 2011 (JP) 2011-155684

(51) **Int. Cl.**

H01L 33/00 (2010.01)

H01L 33/18 (2010.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01L 33/18*** (2013.01); ***H01L 33/0075*** (2013.01); ***H01L 33/20*** (2013.01); *H01L 33/0095* (2013.01); *H01L 33/32* (2013.01)

(58) **Field of Classification Search**

CPC H01L 33/18; H01L 33/0095; H01L 33/20; H01L 33/32; H01L 33/0075

USPC 257/98, 103

See application file for complete search history.

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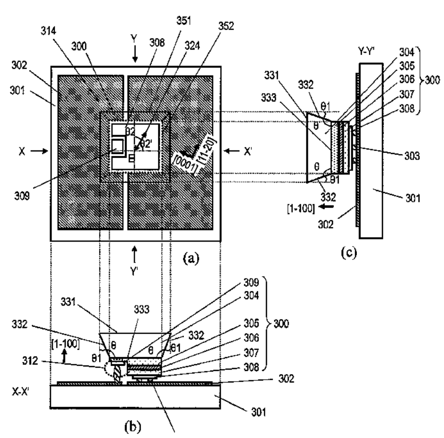
Primary Examiner — Tran Tran

(74) *Attorney, Agent, or Firm* — Renner, Otto, Boisselle & Sklar, LLP

(57) **ABSTRACT**

A nitride-based semiconductor light-emitting element includes a substrate and a nitride semiconductor multilayer structure. The nitride semiconductor multilayer structure includes a nitride semiconductor active layer which emits polarized light. Angle θ, which is formed by at least one of the plurality of lateral surfaces of the substrate with respect to the principal surface of the substrate, is greater than 90°. Angle θ**2** (mod 180°), which is an absolute value of an angle which is formed by an intersecting line of at least one of the plurality of lateral surfaces of the substrate and the principal surface of the substrate with respect to a polarization direction in the principal surface of the polarized light, is an angle which does not include 0° or 90°.

18 Claims, 34 Drawing Sheets



(51) **Int. Cl.**
H01L 33/20 (2010.01)
H01L 33/32 (2010.01)

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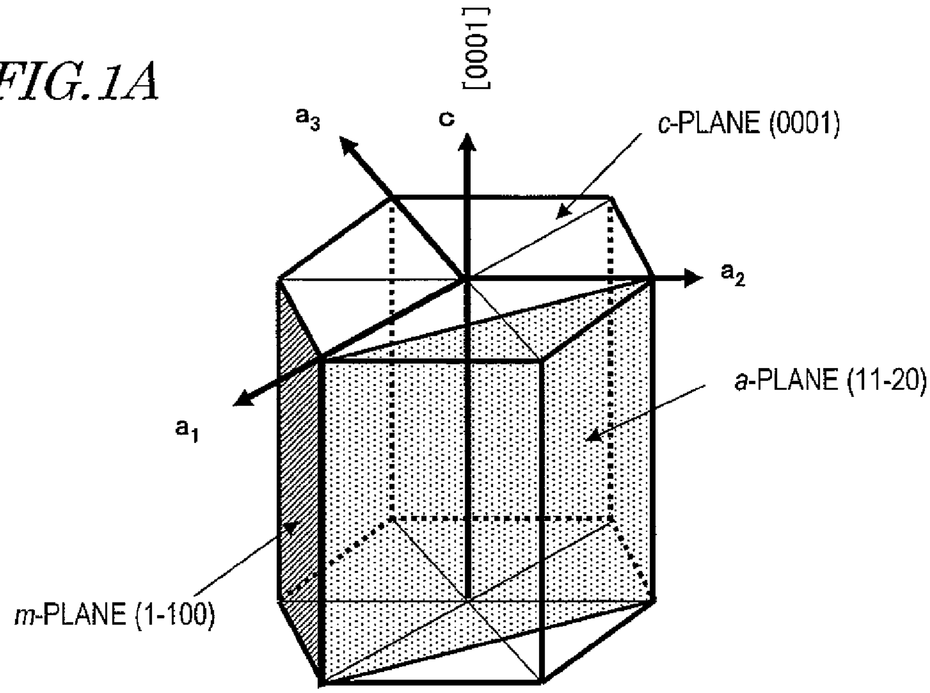
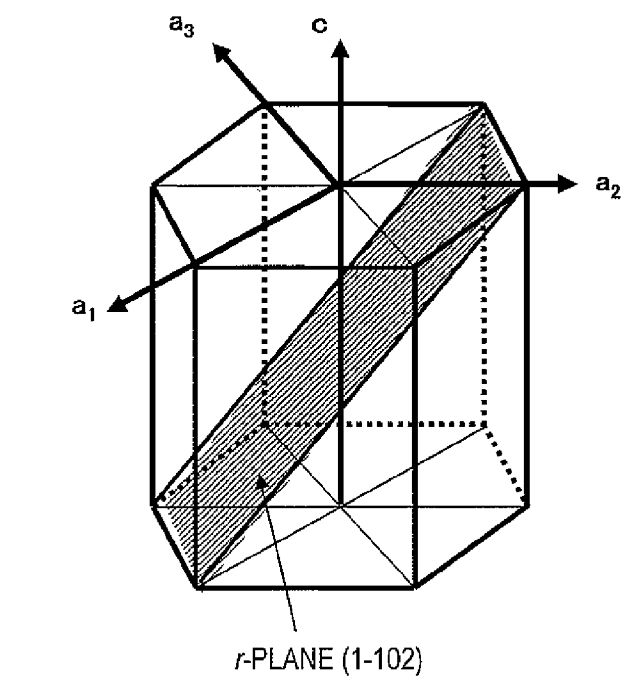
FIG.1A



[0001]
a3
c
c-PLANE (0001)
a2
a1
a-PLANE (11-20)
m-PLANE (1-100)

FIG.1B



a3
c
a2
a1
r-PLANE (1-102)

FIG.1C

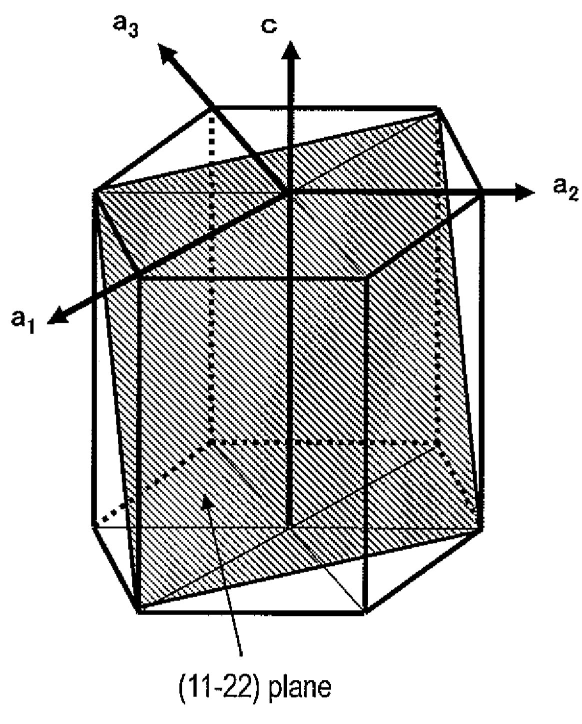


FIG.2A

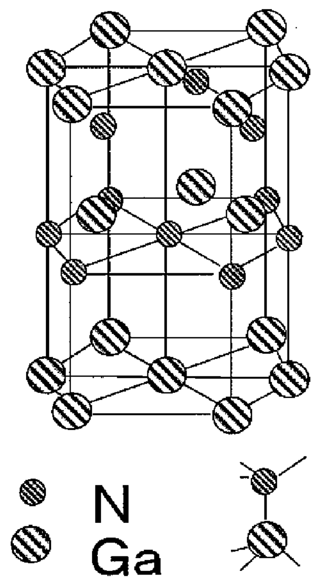


FIG.2B

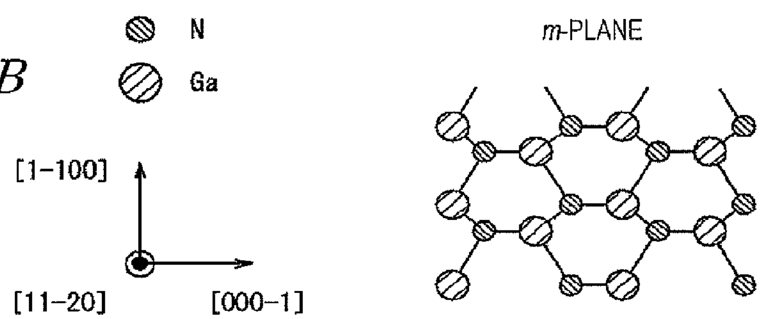


FIG.2C

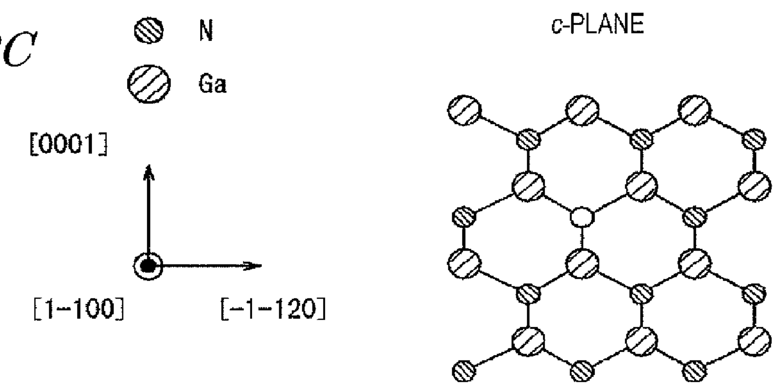
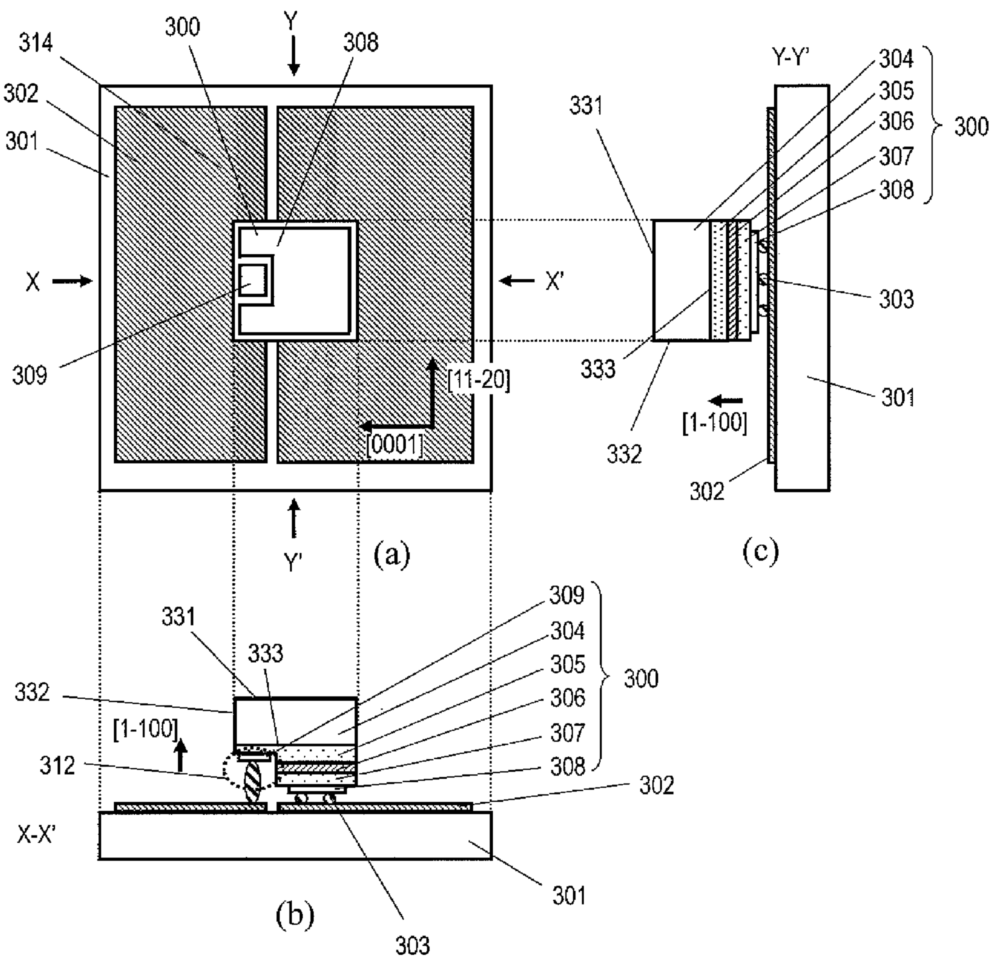


FIG.3



Y
300
314
308
302
301
X
X'
309
[11-20]
[0001]
Y'
(a)
Y-Y'
331
304
305
306
307
308
300
303
333
[1-100]
301
332
302
(c)
331
333
332
[1-100]
312
309
304
305
306
307
308
300
302
X-X'
301
(b)
303

FIG.4

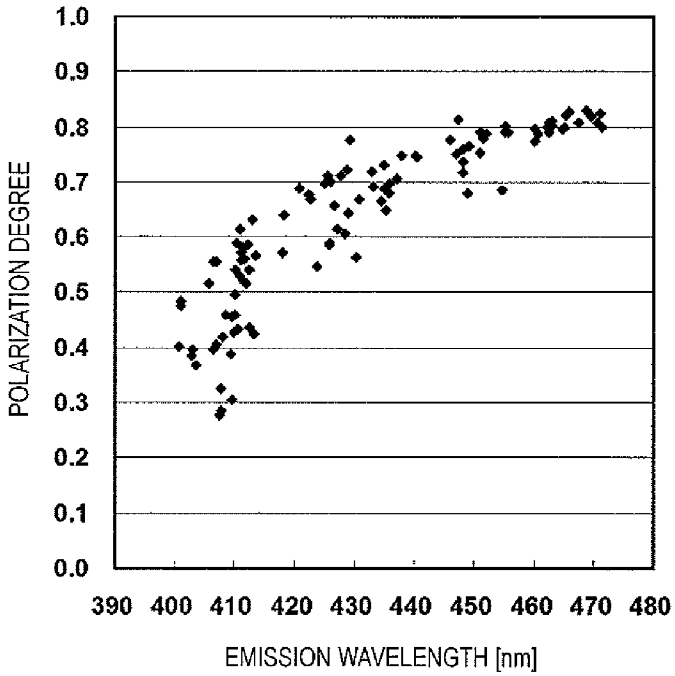

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
POLARIZATION DEGREE
390 400 410 420 430 440 450 460 470 480
EMISSION WAVELENGTH [nm]

FIG.5

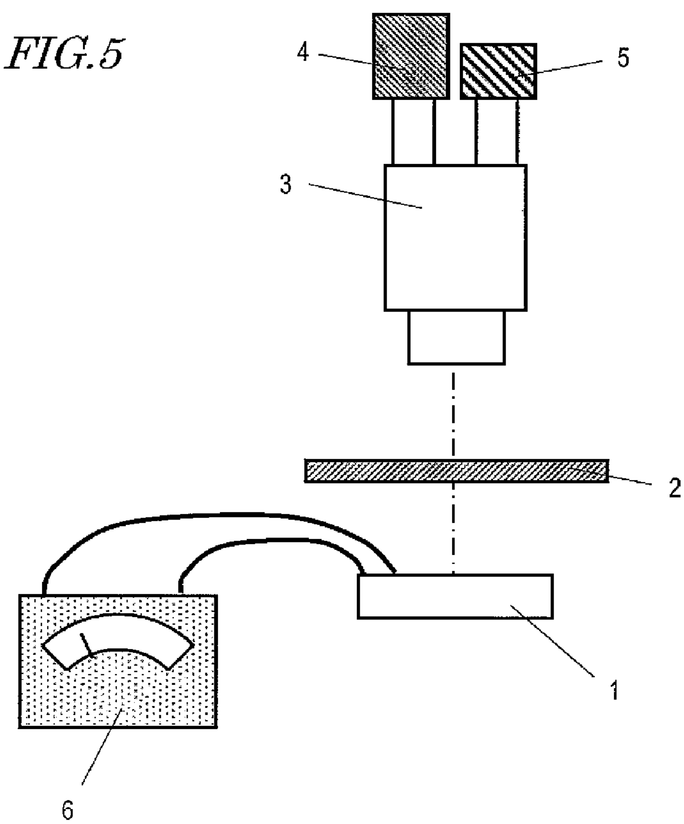
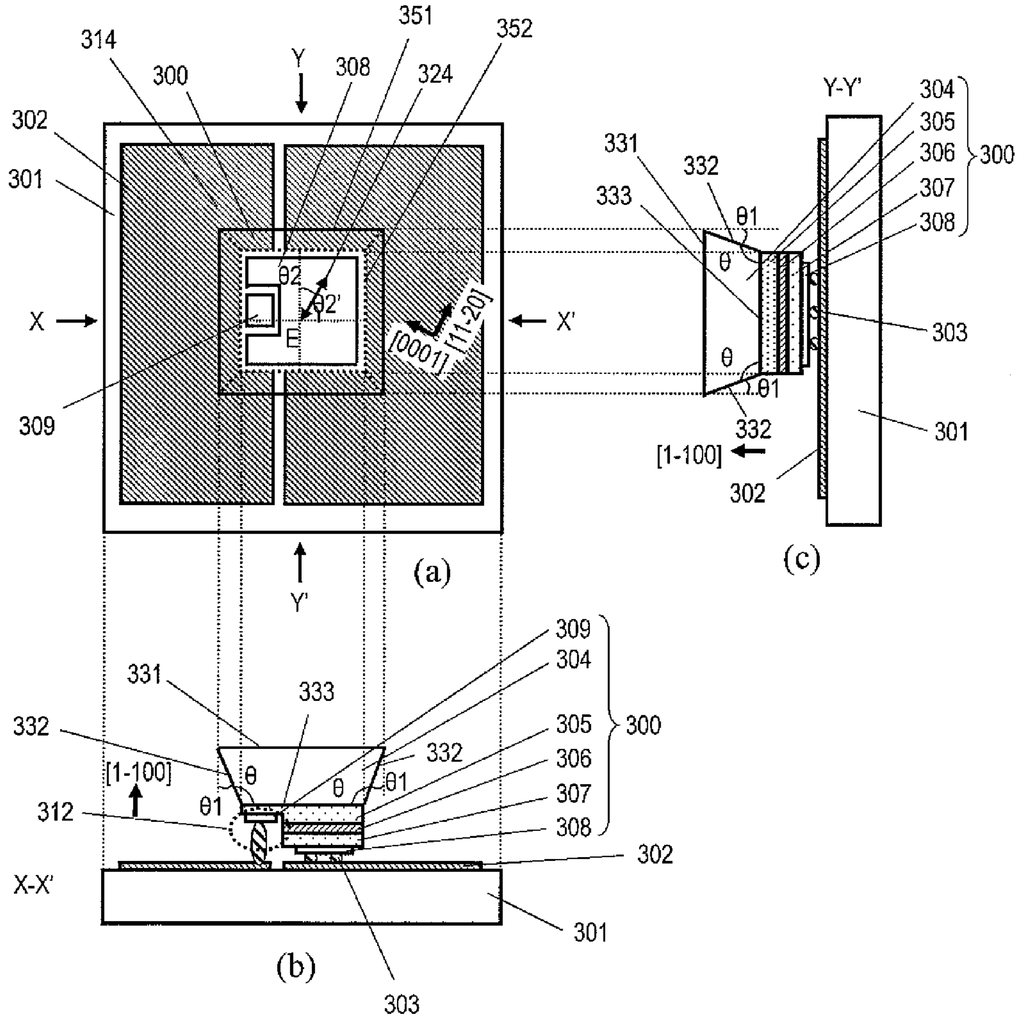

4
5
3
2
1
6

FIG.6



314
300
Y
308
351
324
352
302
301
θ2
θ2'
E
[0001]
[11-20]
X
X'
309
Y'
(a)
Y-Y'
304
305
306
307
308
300
331
332
333
θ1
θ
θ
θ1
303
332
[1-100]
301
302
(c)
309
304
331
333
305
300
332
332
θ
θ
θ1
[1-100]
306
312
θ1
307
308
302
X-X'
301
(b)
303

FIG. 7A

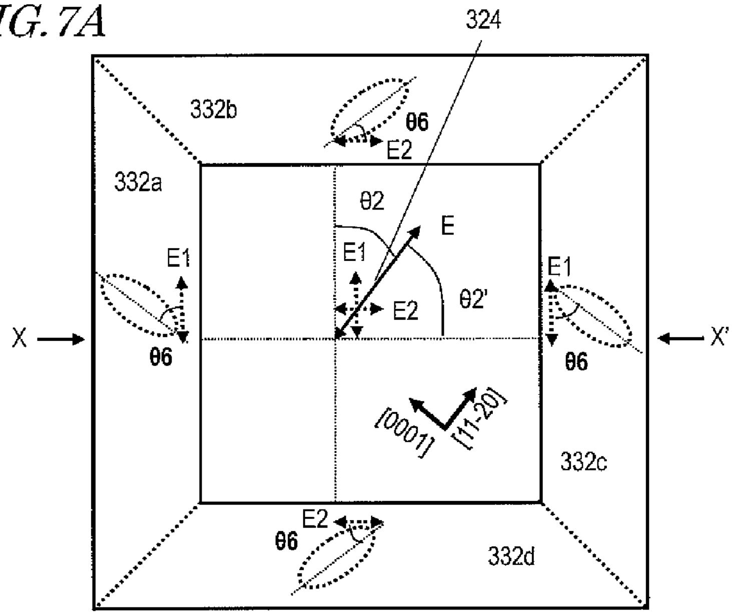


FIG. 7B

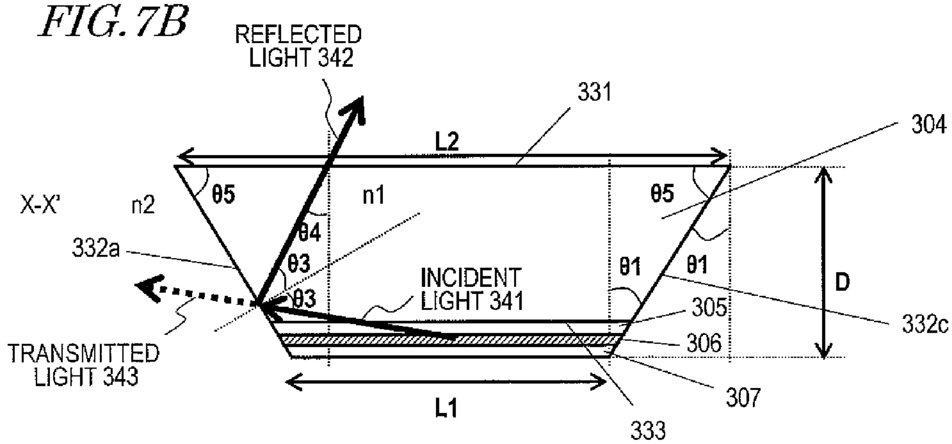


FIG. 7C

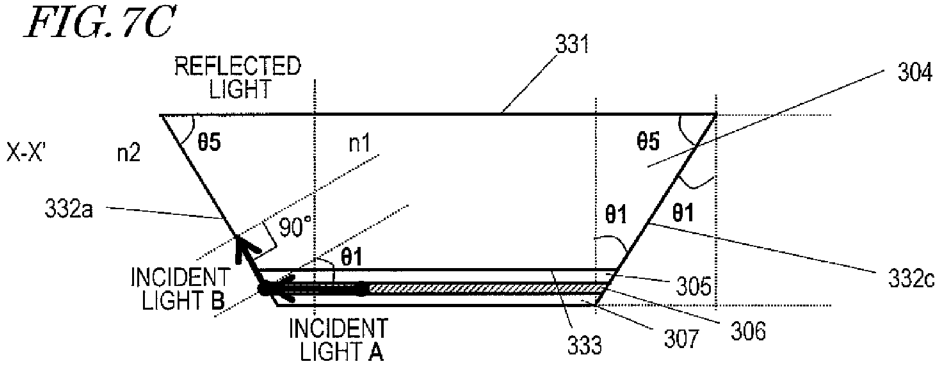


FIG.8A

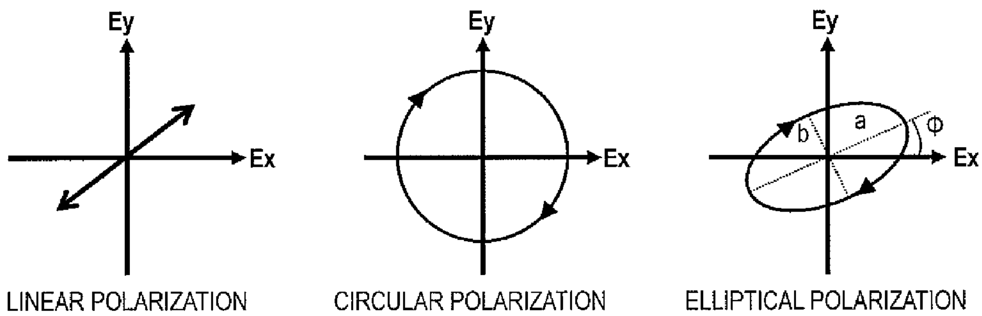


FIG.8B

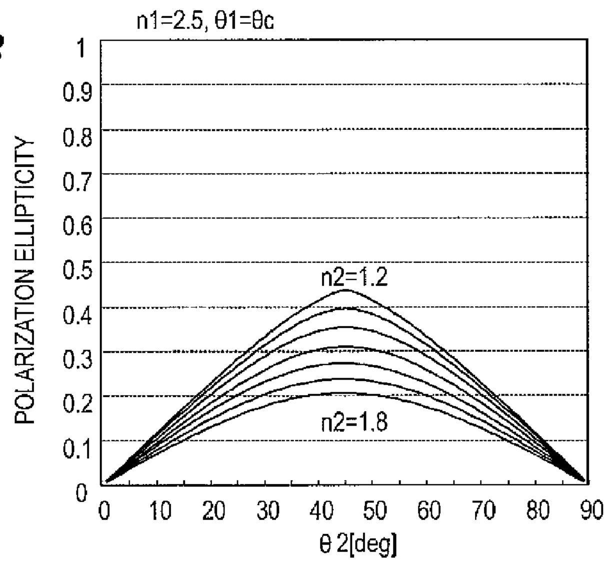


FIG.8C

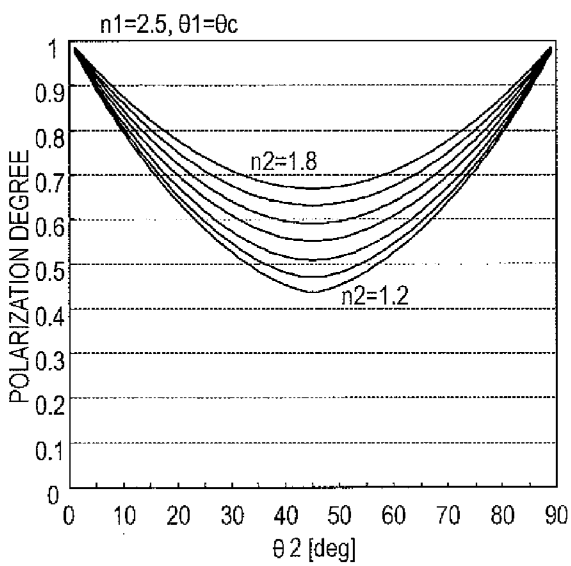
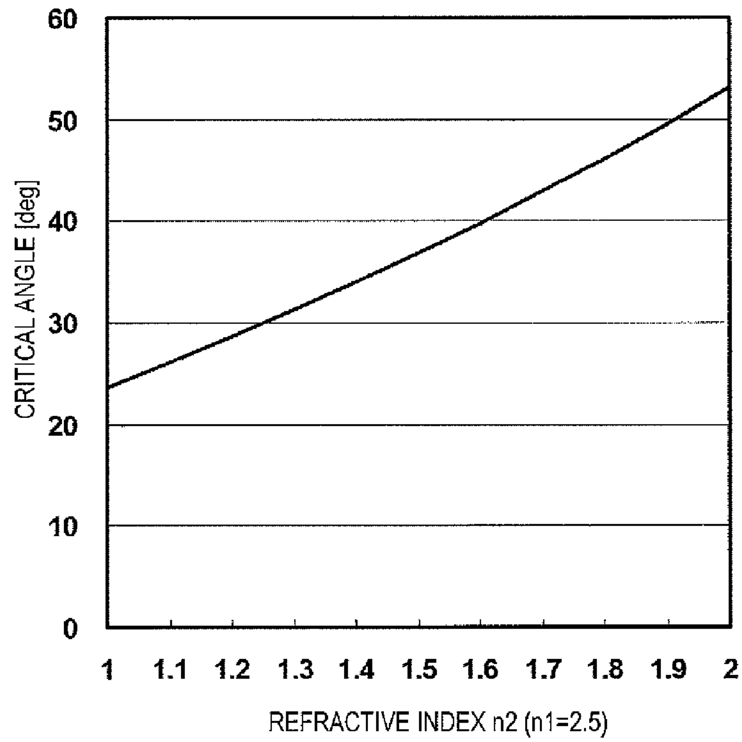
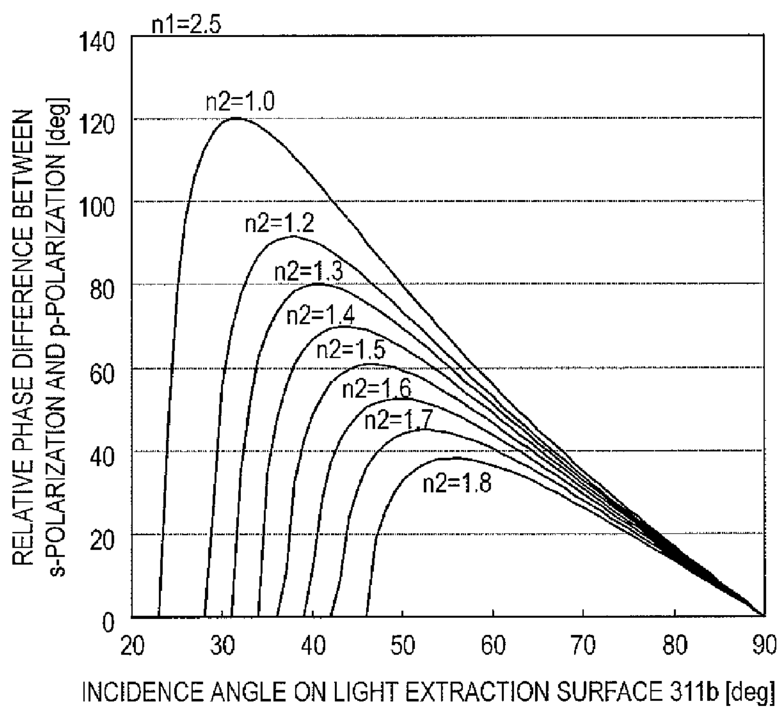


FIG.9A



60
50
40
30
20
10
0
CRITICAL ANGLE [deg]
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
REFRACTIVE INDEX n2 (n1=2.5)

FIG.9B



n1=2.5
140
120
100
80
60
40
20
0
n2=1.0
n2=1.2
n2=1.3
n2=1.4
n2=1.5
n2=1.6
n2=1.7
n2=1.8
RELATIVE PHASE DIFFERENCE BETWEEN s-POLARIZATION AND p-POLARIZATION [deg]
20
30
40
50
60
70
80
90
INCIDENCE ANGLE ON LIGHT EXTRACTION SURFACE 311b [deg]

FIG. 10A

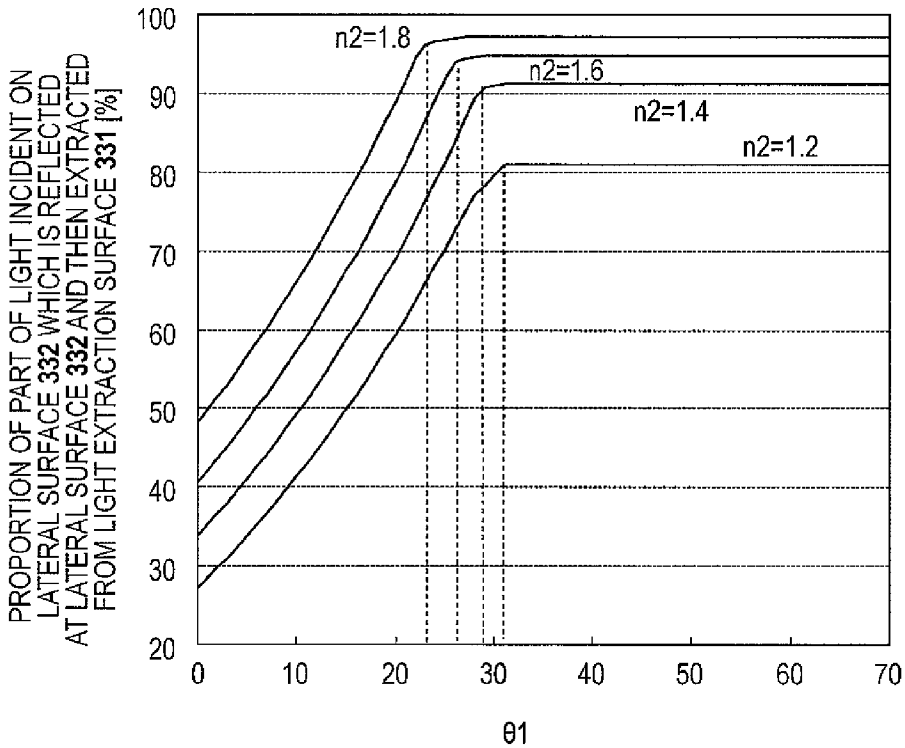


FIG. 10B

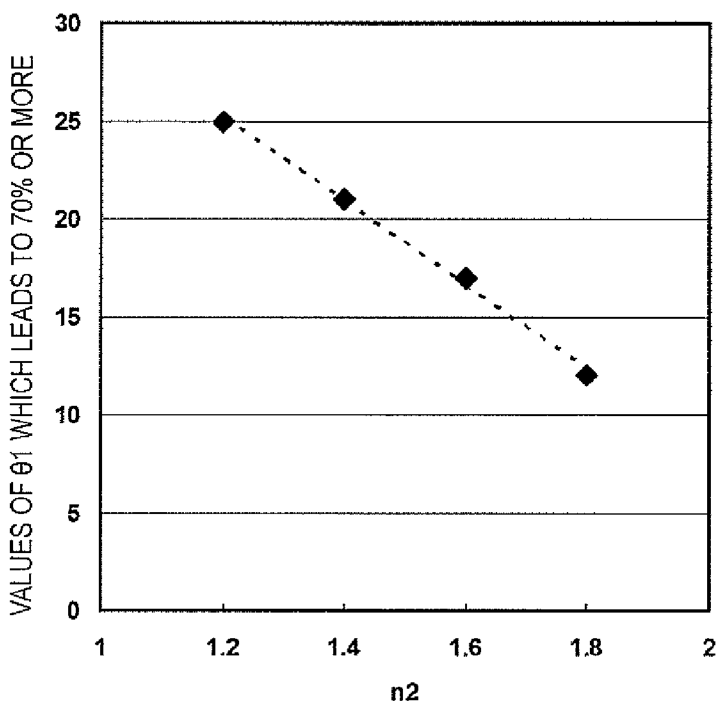
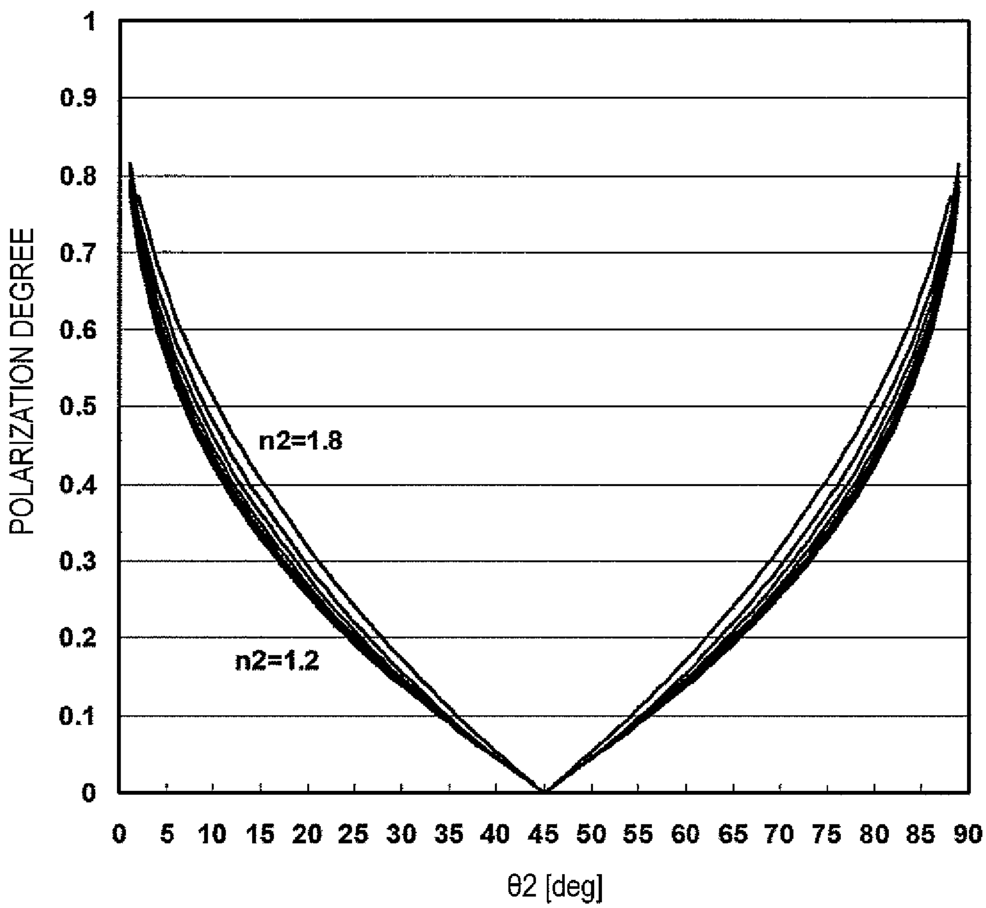


FIG.11



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
POLARIZATION DEGREE
n2=1.8
n2=1.2
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
θ2 [deg]

FIG. 12A

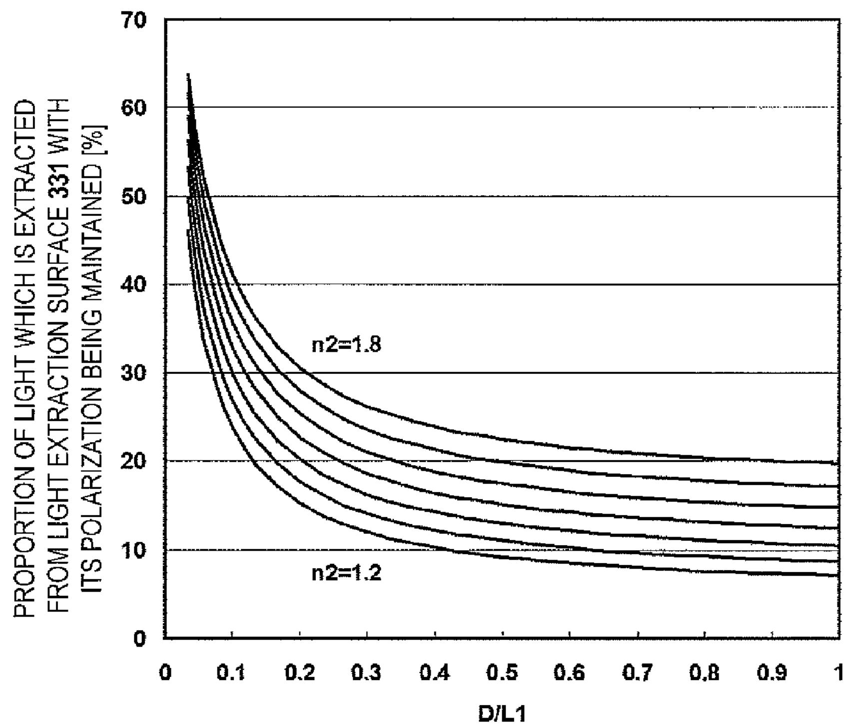


FIG. 12B

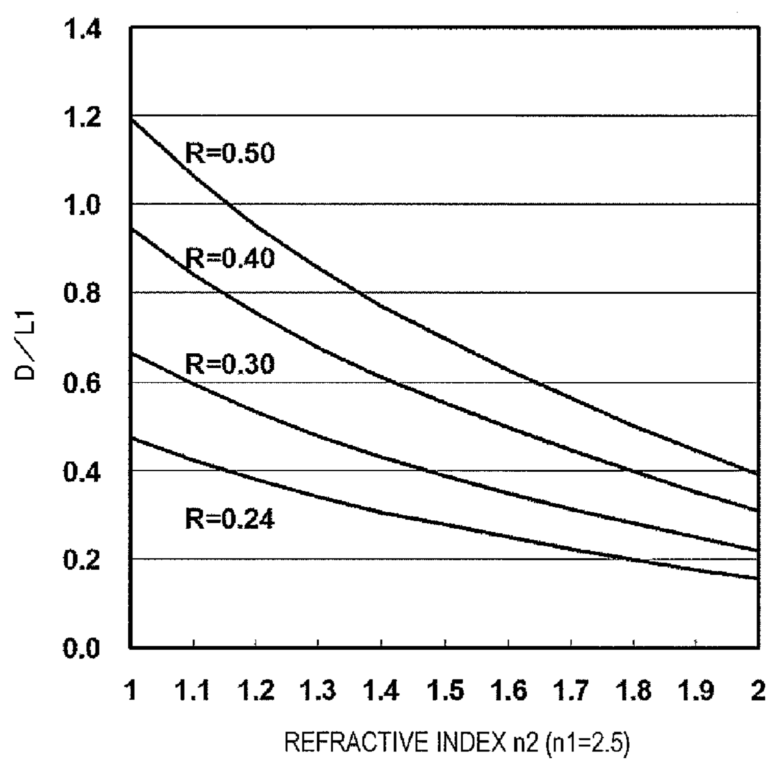


FIG.13

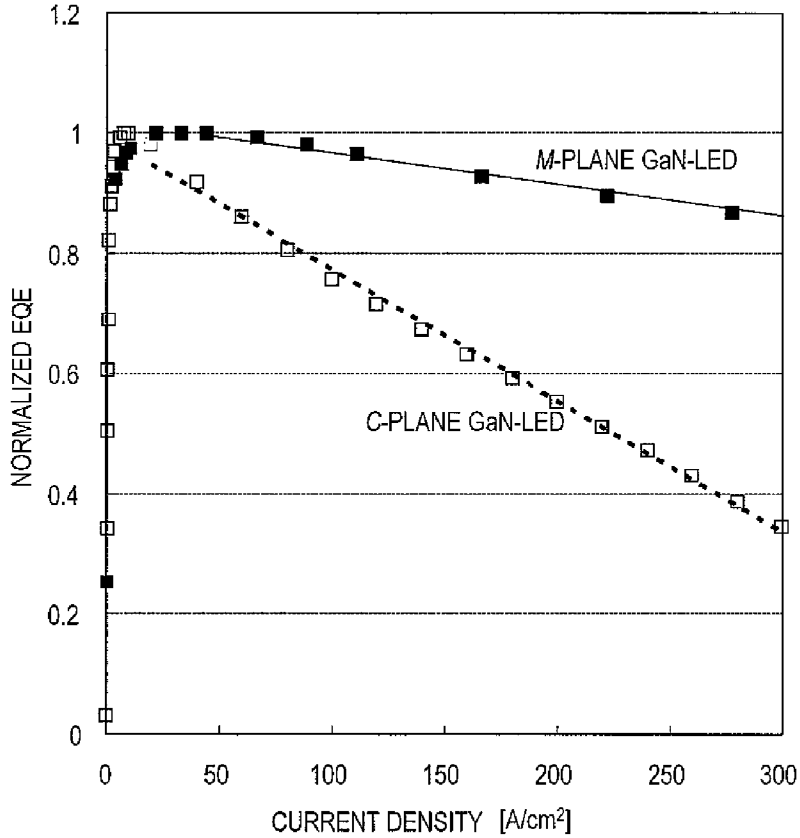


FIG.14A

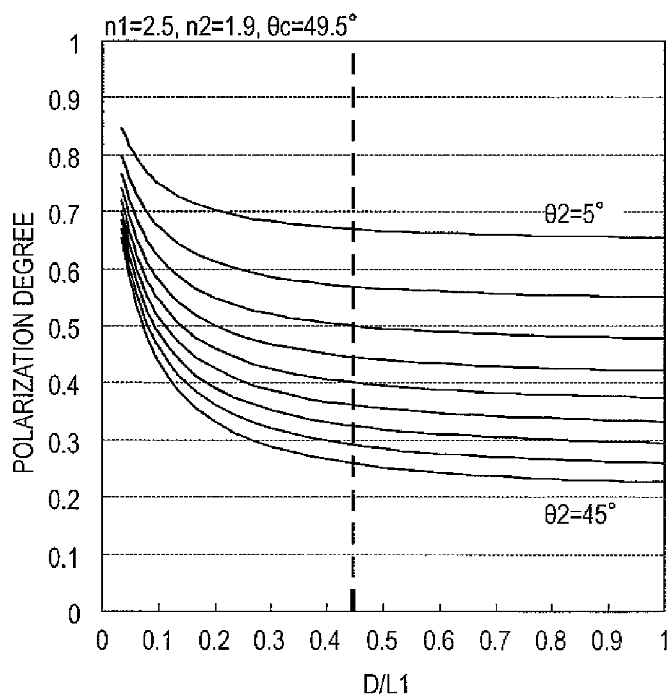


FIG.14B

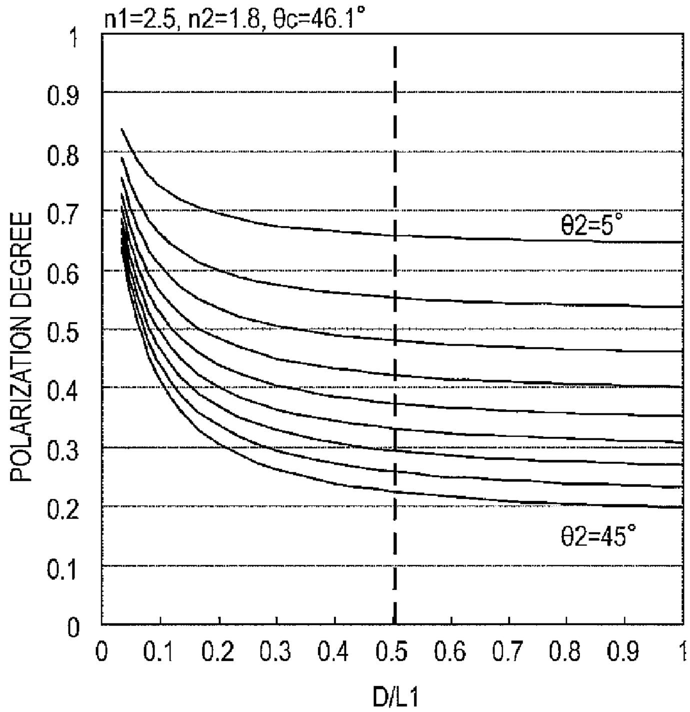


FIG.14C

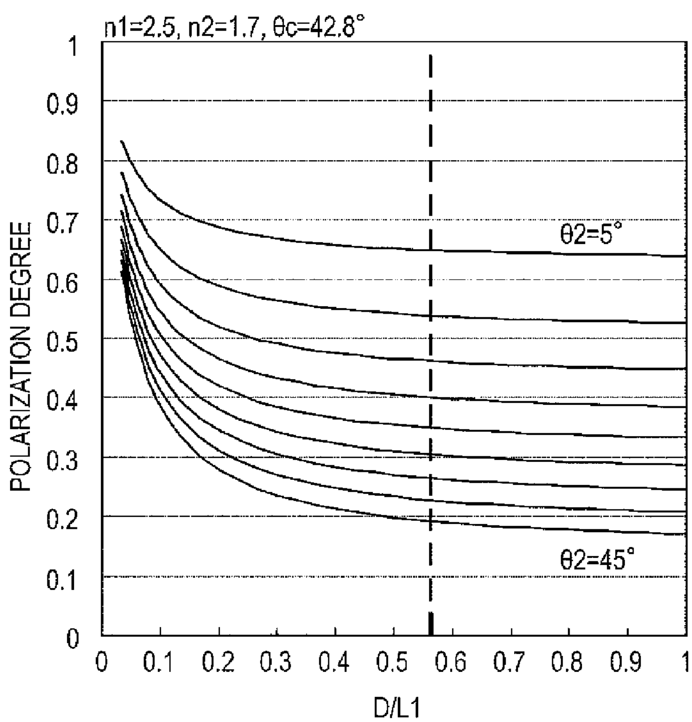


FIG.14D

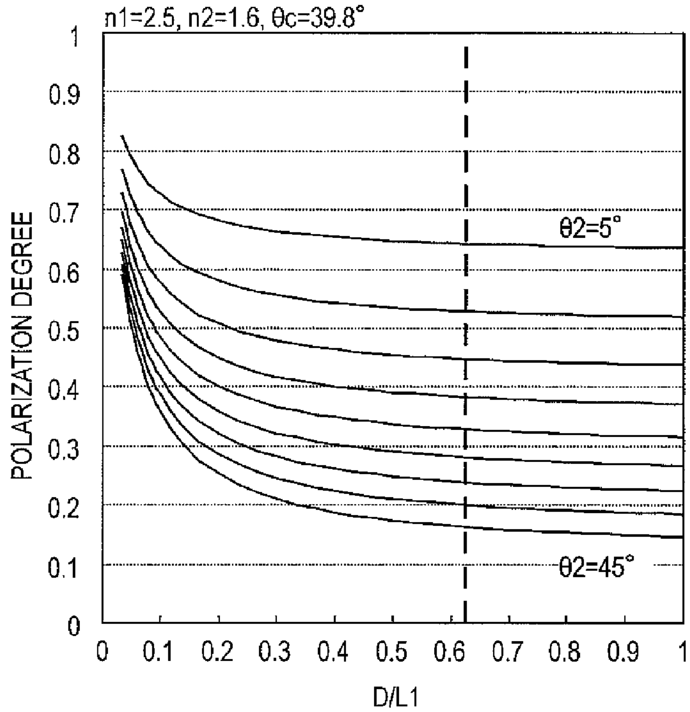


FIG.14E

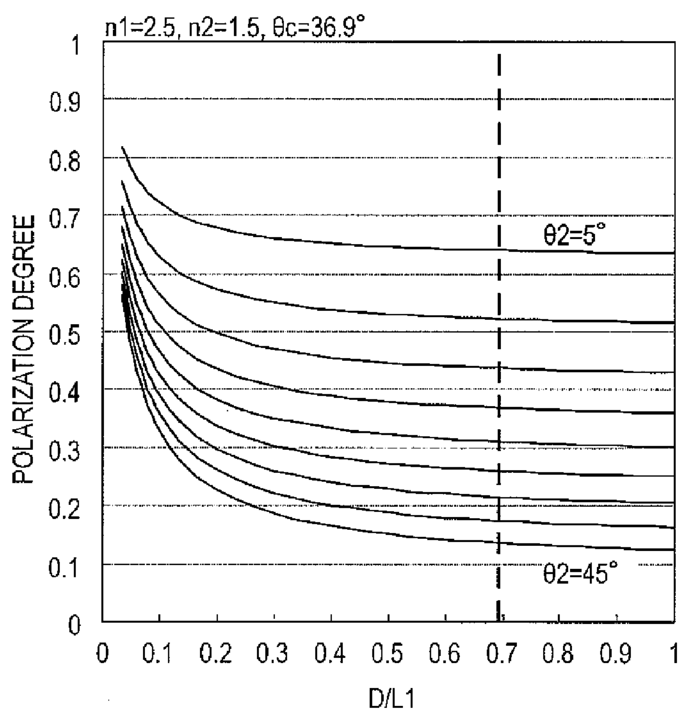


FIG. 14F

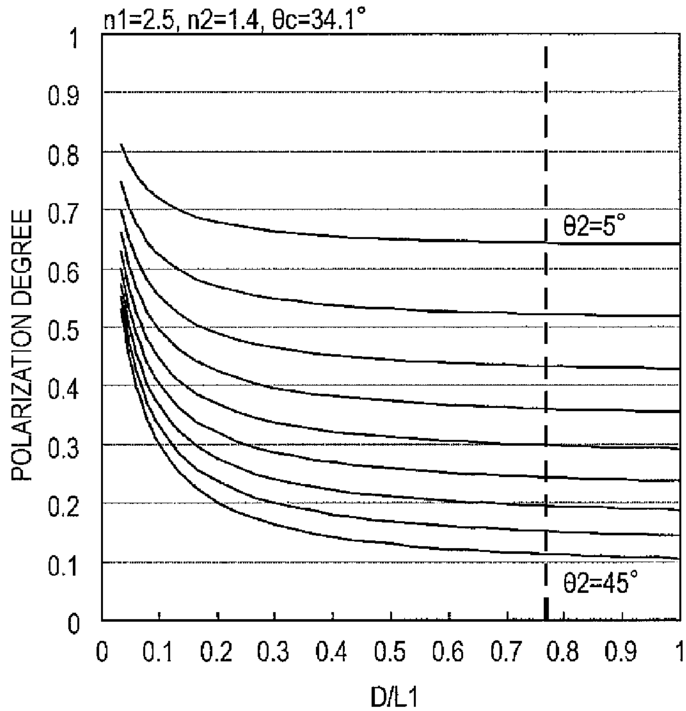


FIG. 14G

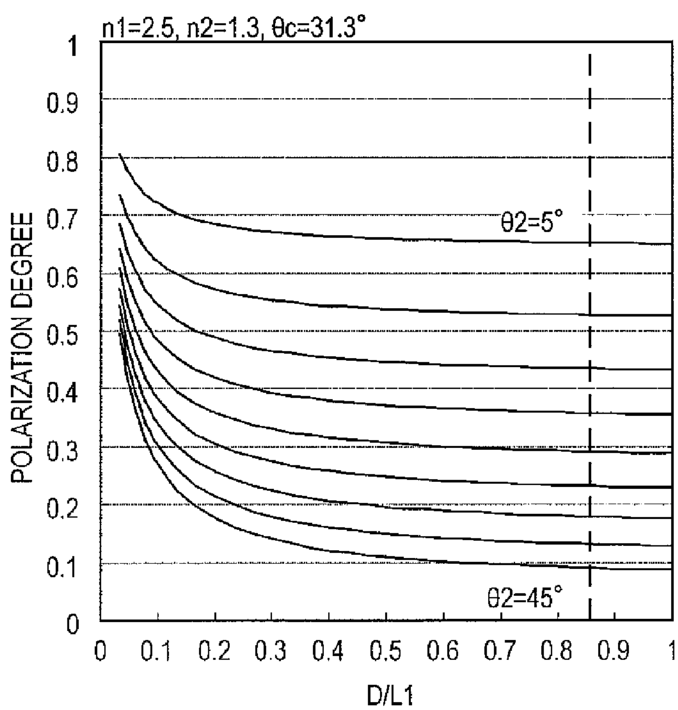


FIG.14H

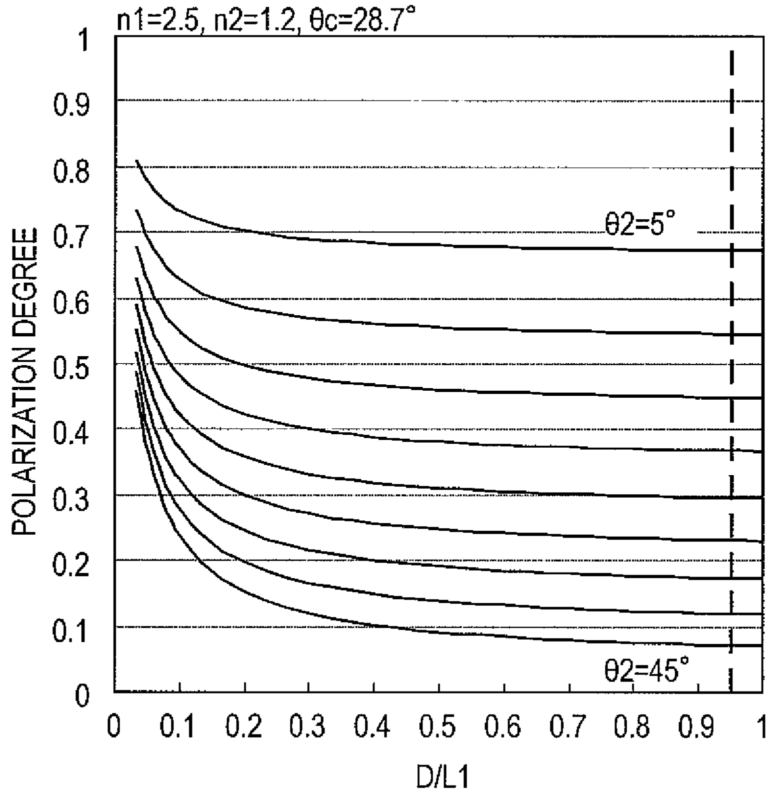

n1=2.5, n2=1.2, θc=28.7°
POLARIZATION DEGREE
θ2=5°
θ2=45°
D/L1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

FIG. 15

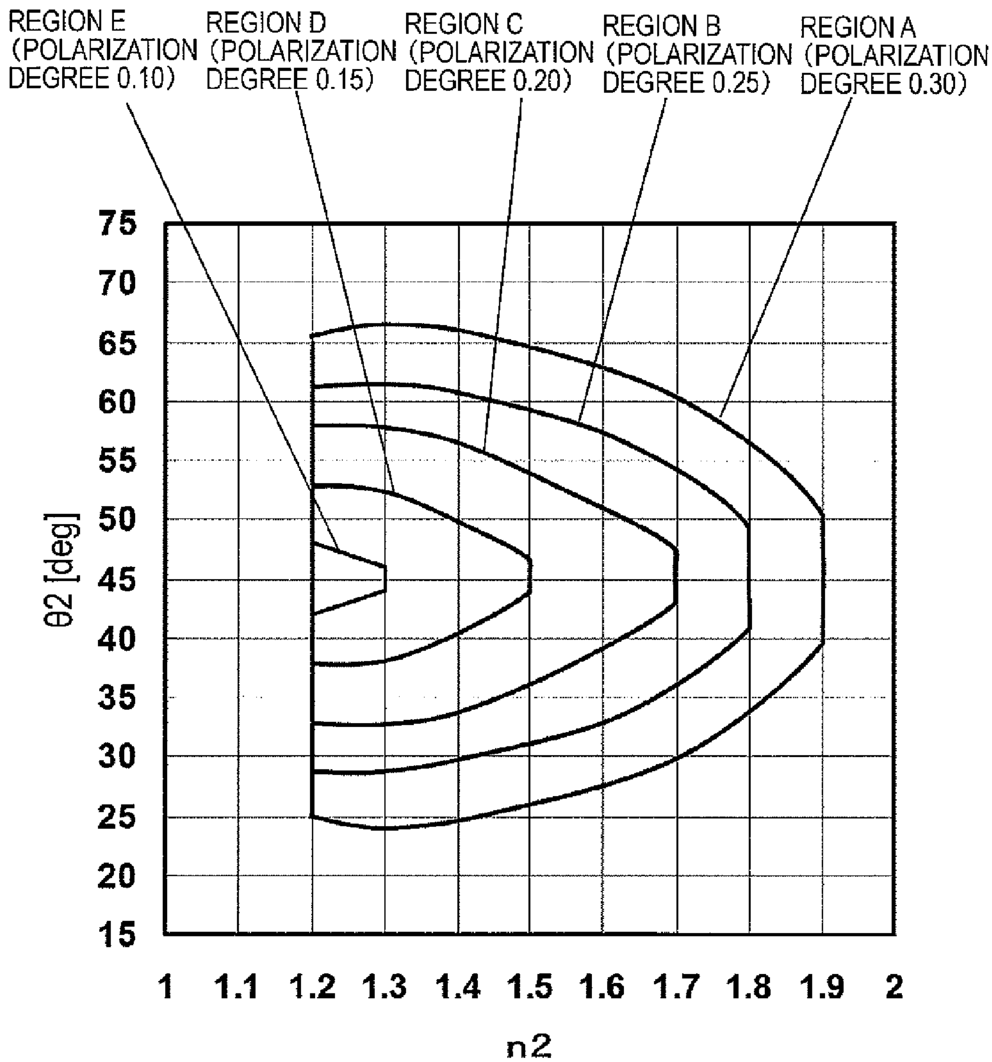

REGION E (POLARIZATION DEGREE 0.10)
REGION D (POLARIZATION DEGREE 0.15)
REGION C (POLARIZATION DEGREE 0.20)
REGION B (POLARIZATION DEGREE 0.25)
REGION A (POLARIZATION DEGREE 0.30)
75
70
65
60
55
50
45
40
35
30
25
20
15
θ2 [deg]
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
n2

FIG.16

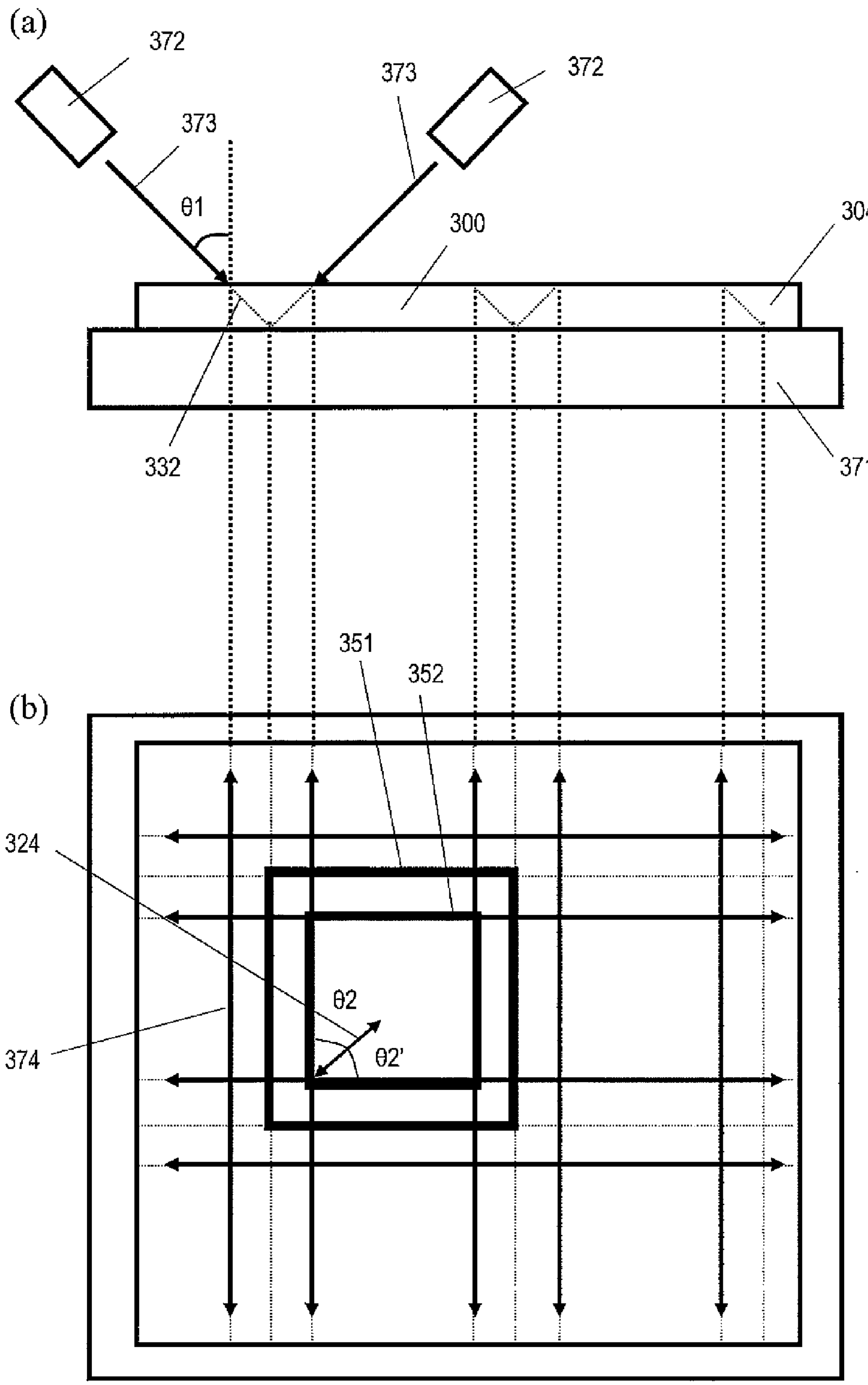


FIG.17

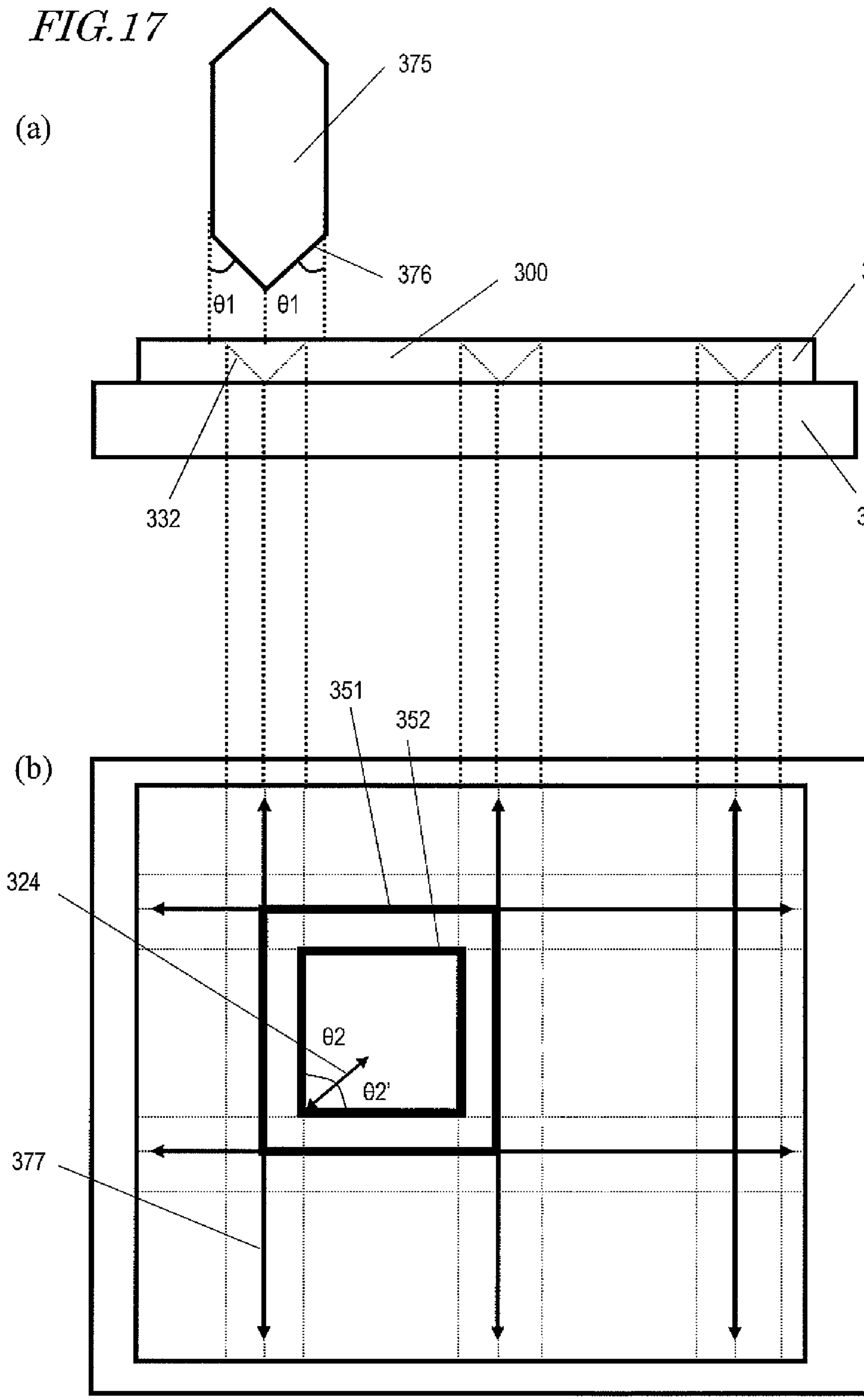


FIG. 18A

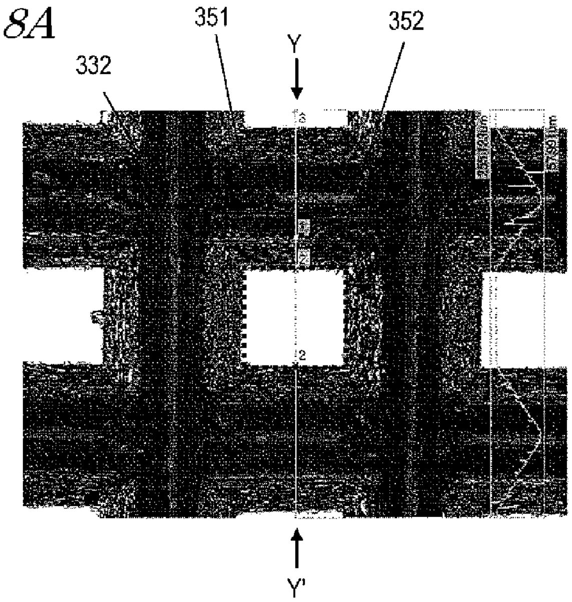


FIG. 18B

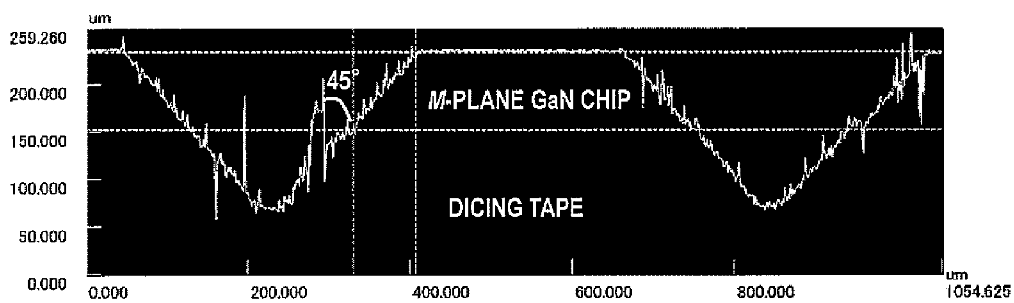
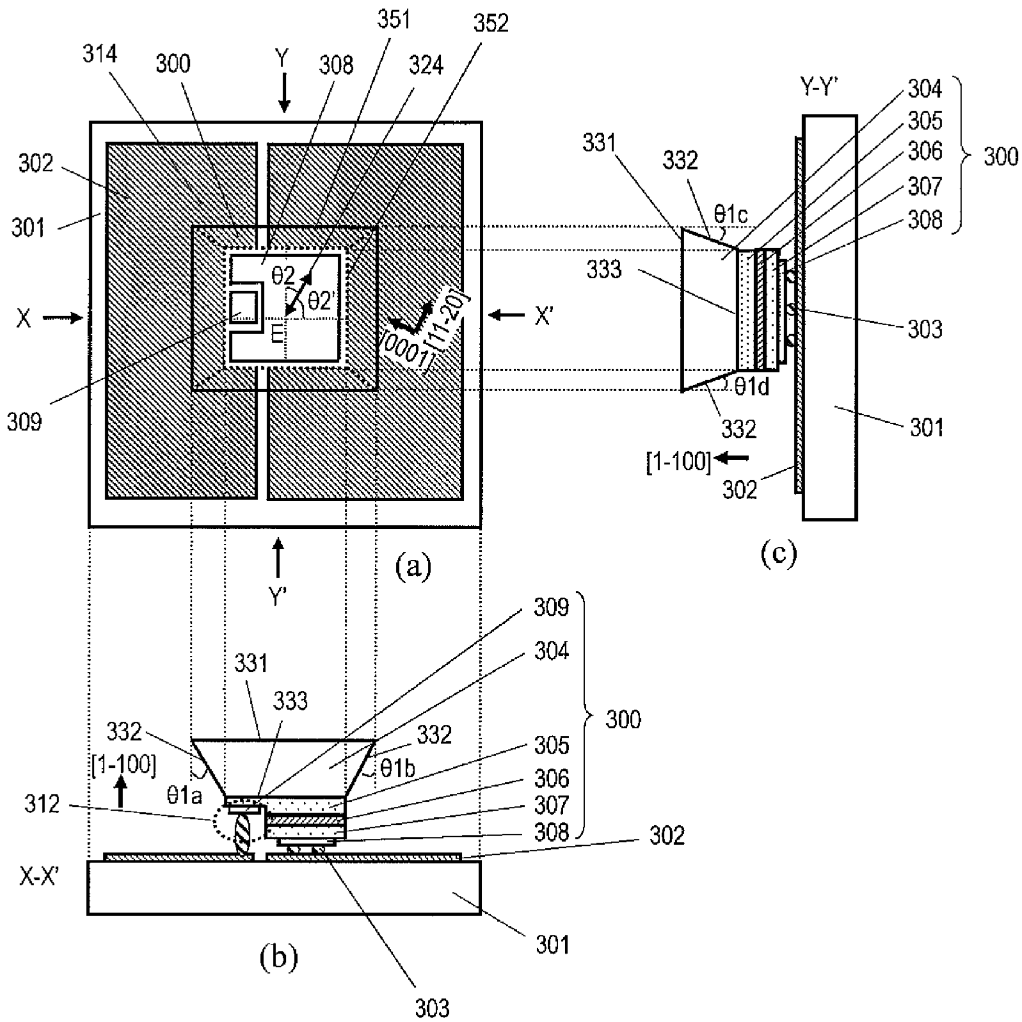


FIG.19



351
352
314
300
Y
308
324
302
301
θ2
θ2'
X
X'
E
[11-20]
[0001]
309
Y'
(a)
Y-Y'
304
305
306
307
308
300
331
332
θ1c
333
303
θ1d
332
301
[1-100]
302
(c)
309
304
331
333
300
332
332
[1-100]
θ1a
θ1b
305
306
307
308
312
302
X-X'
301
(b)
303

FIG.20

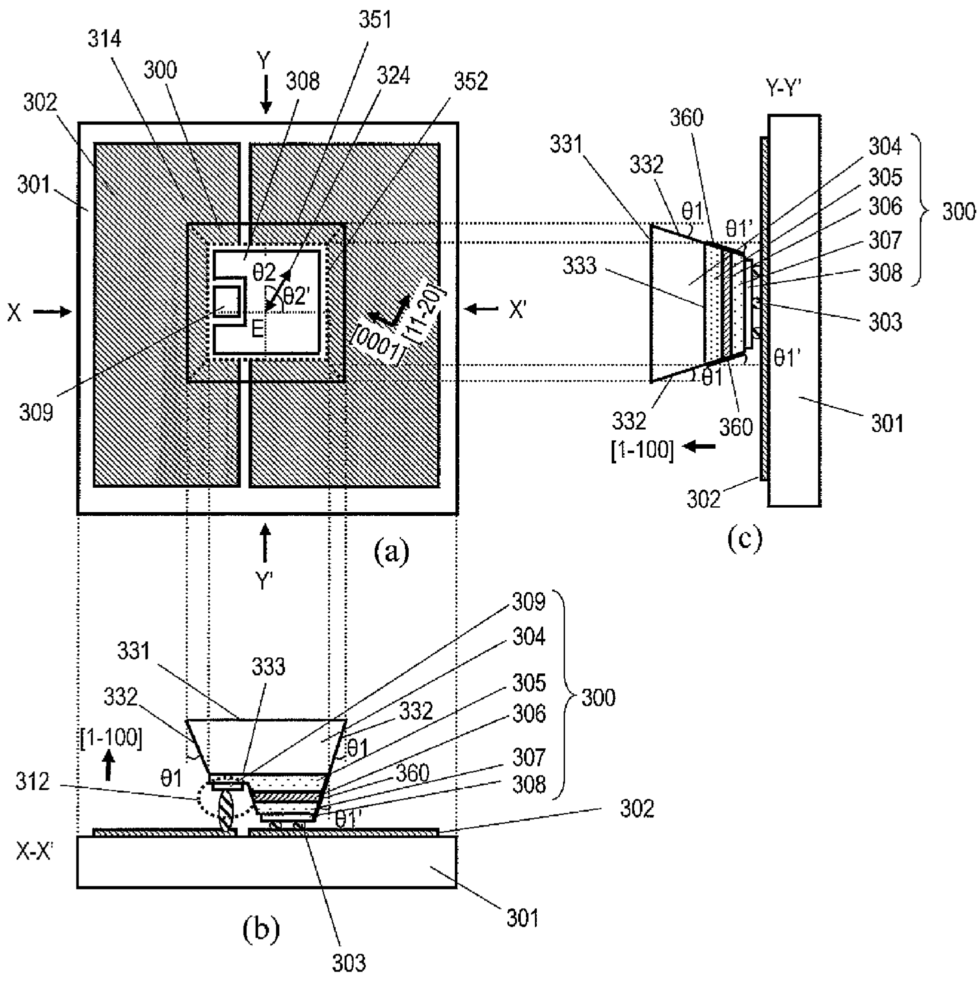
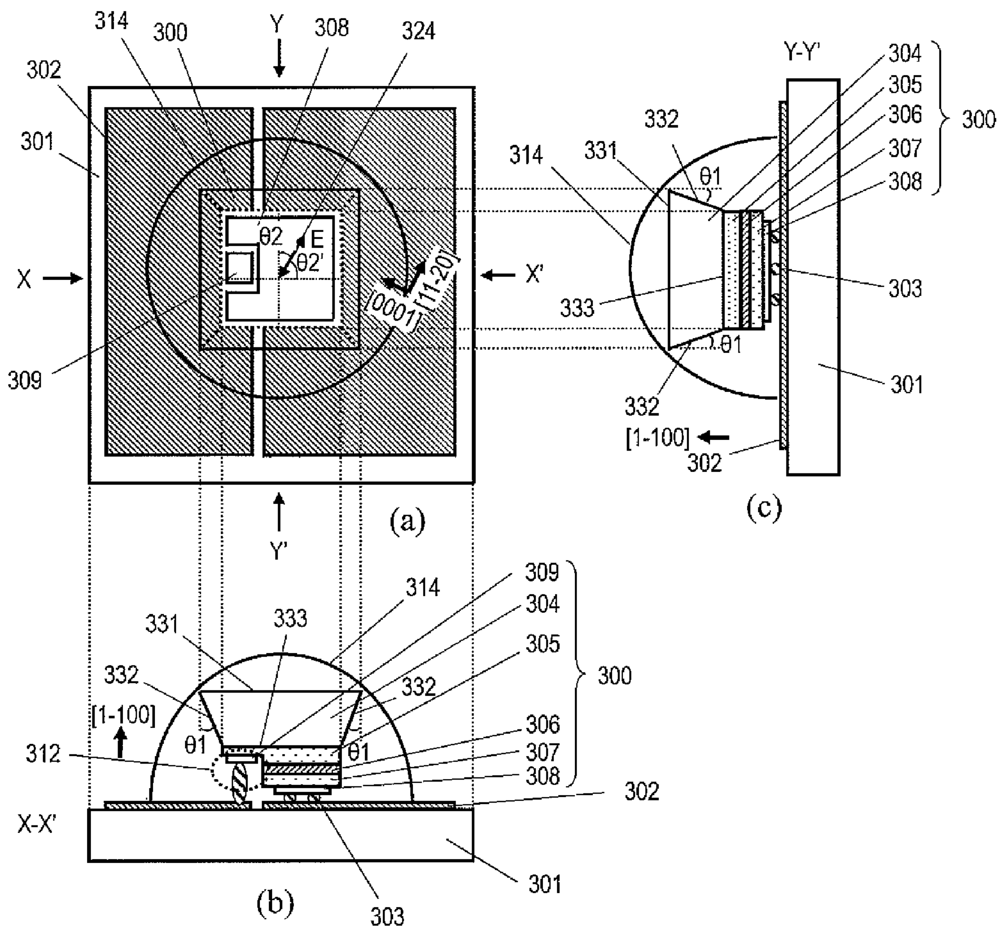

351
314
300
Y
308
324
352
302
301
X
X'
θ2
θ2'
E
[11-20]
[0001]
309
Y'
(a)
Y-Y'
360
331
332
304
305
306
307
308
300
θ1
θ1'
333
303
θ1'
332
360
301
[1-100]
302
(c)
309
331
333
304
332
305
300
332
306
[1-100]
θ1
307
360
312
θ1
308
θ1'
302
X-X'
301
(b)
303

FIG.21



314
300
Y
308
324
302
301
θ2
E
θ2'
X
X'
[11-20]
[0001]
309
(a)
Y'
Y-Y'
304
305
306
307
308
300
332
314
331
θ1
333
303
θ1
332
301
[1-100]
302
(c)
309
314
304
331
333
305
300
332
332
[1-100]
θ1
θ1
306
312
307
308
302
X-X'
301
(b)
303

FIG.22

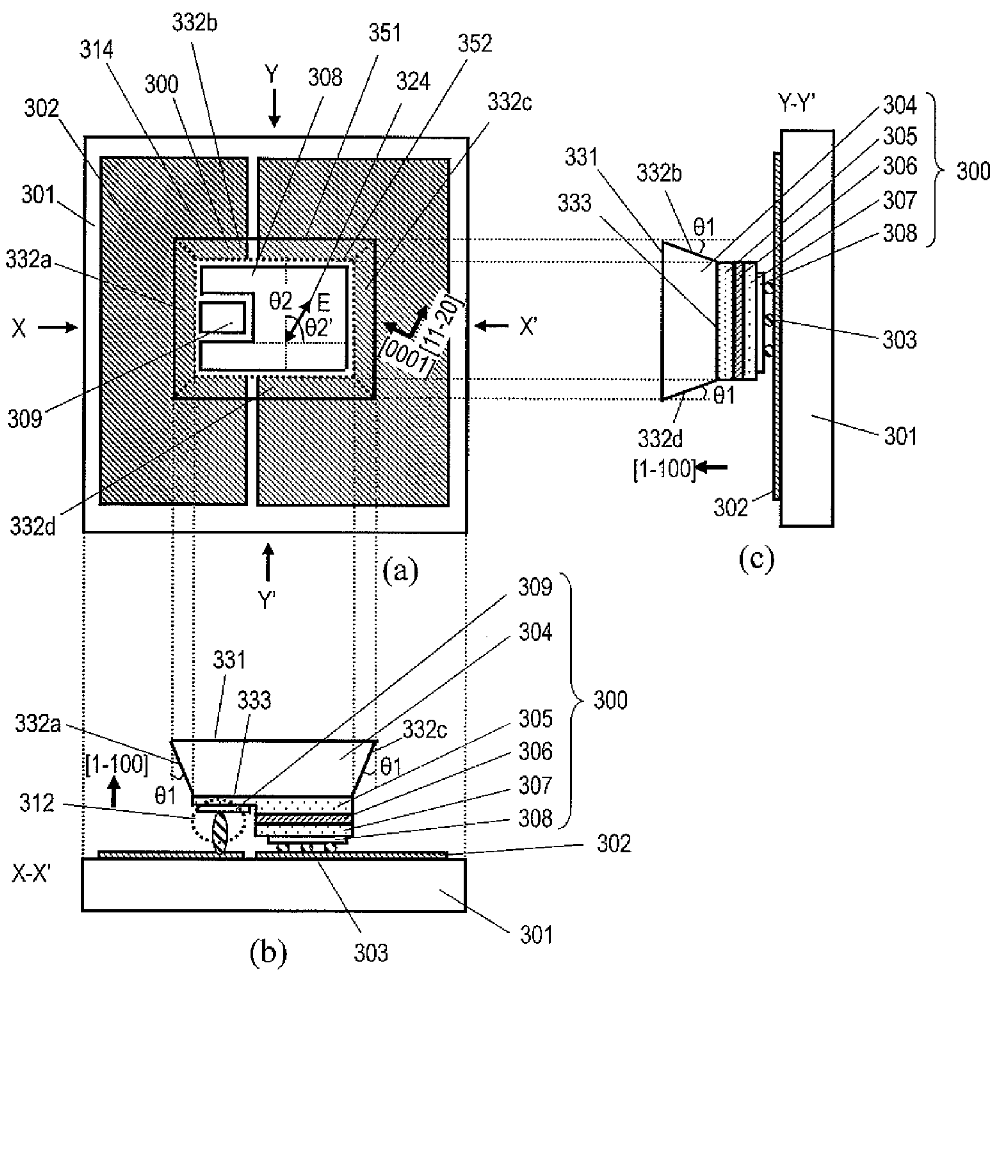

332b
351
352
314
300
308
324
332c
302
Y
301
332a
θ2
E
θ2'
X
X'
[0001]
[11-20]
309
332d
(a)
Y'
Y-Y'
304
305
306
307
308
300
331
332b
333
θ1
303
θ1
332d
[1-100]
301
302
(c)
309
304
331
333
332a
332c
[1-100]
θ1
θ1
312
305
306
307
308
300
302
X-X'
301
(b)
303

FIG.23

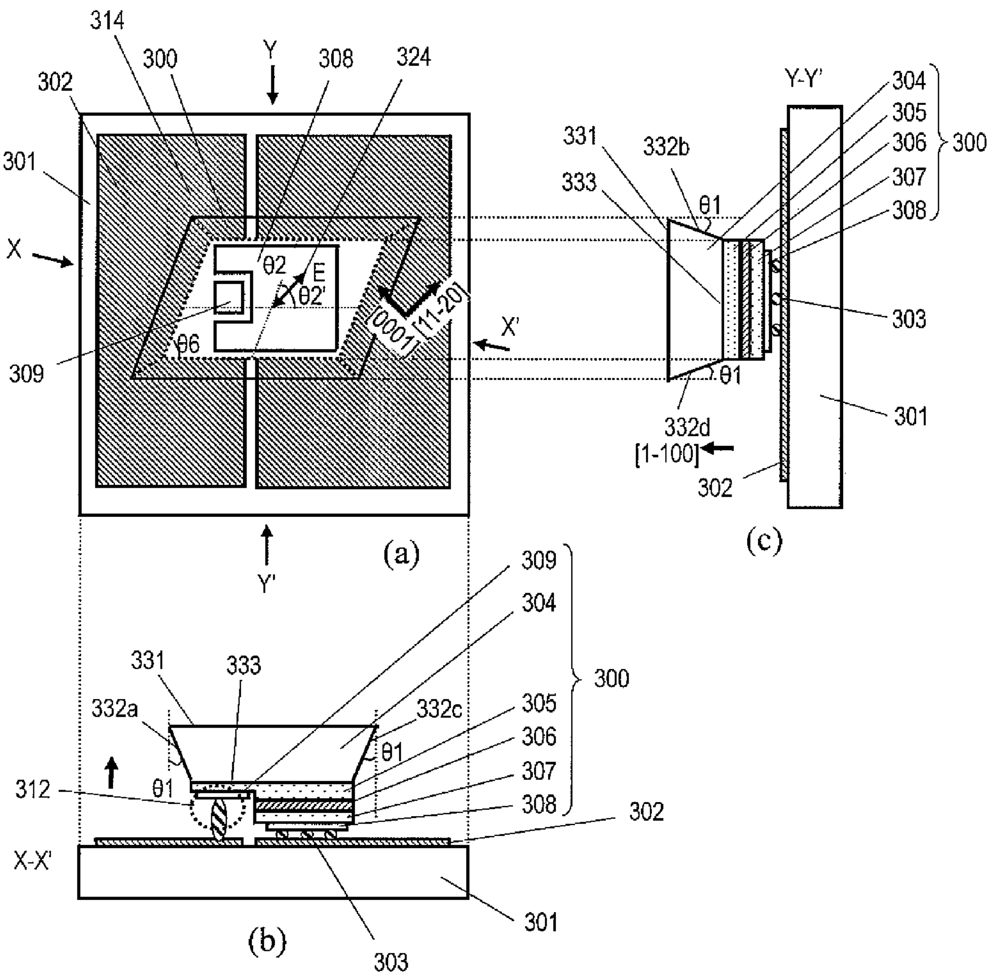

314
300
Y
308
324
302
301
X
θ2
E
θ2'
[0001]
[11-20]
X'
309
θ6
Y'
(a)
Y-Y'
304
305
306
300
307
308
331
332b
θ1
333
303
θ1
301
332d
[1-100]
302
(c)
309
304
331
333
300
332a
332c
305
θ1
306
312
θ1
307
308
302
X-X'
301
(b)
303

FIG.24

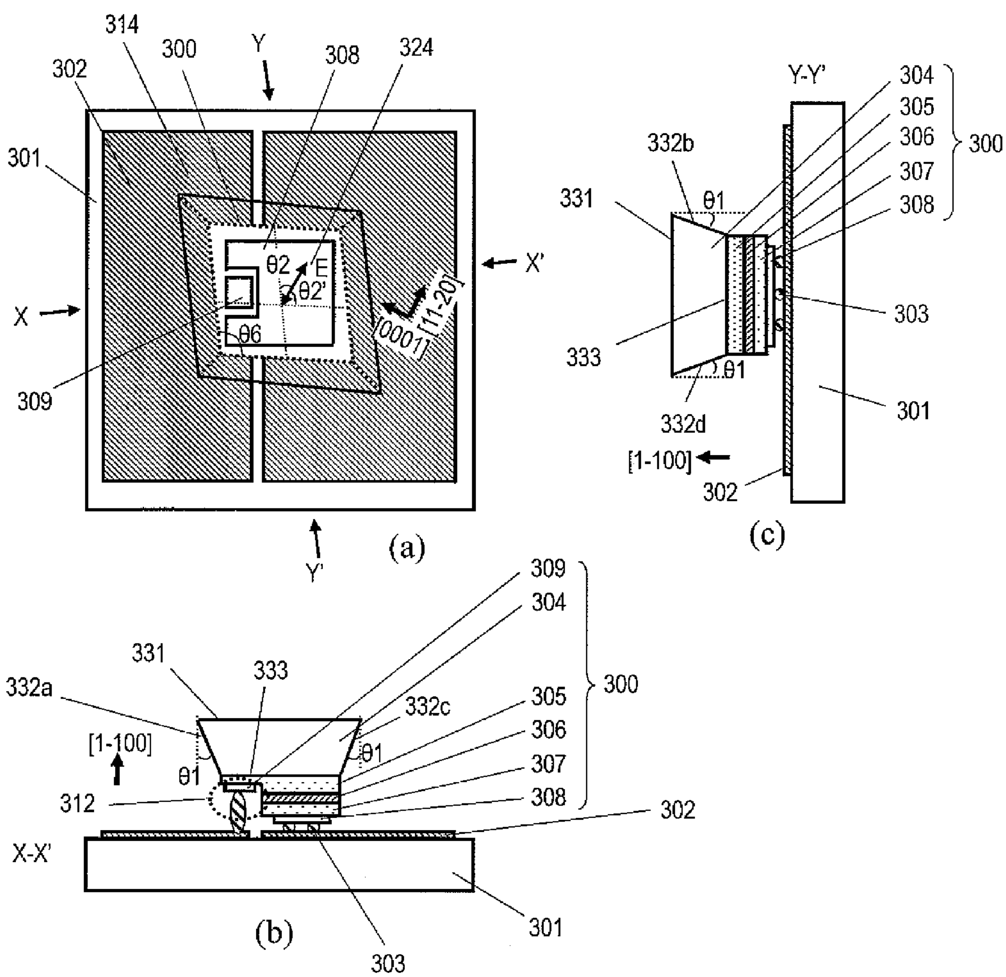
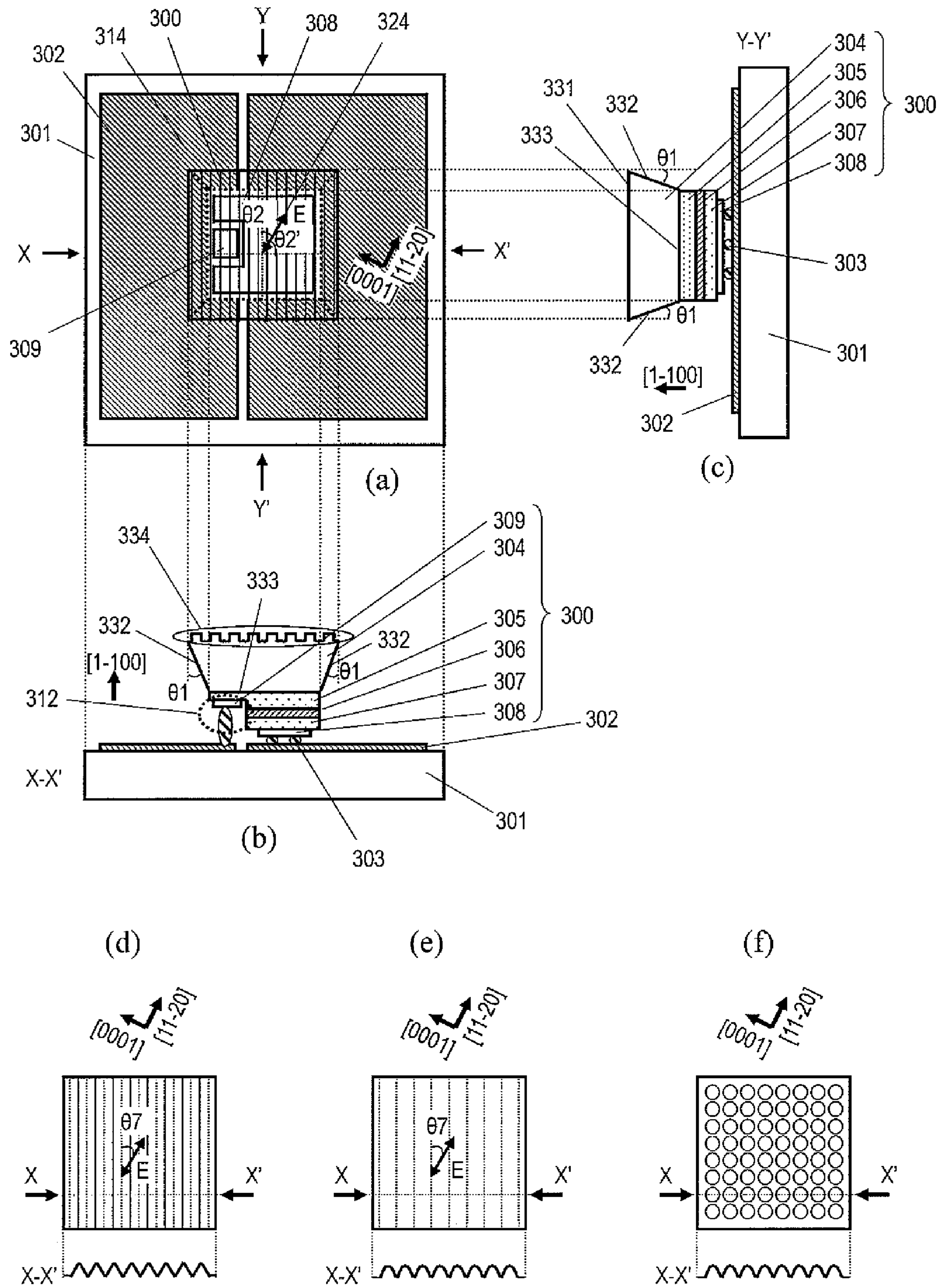
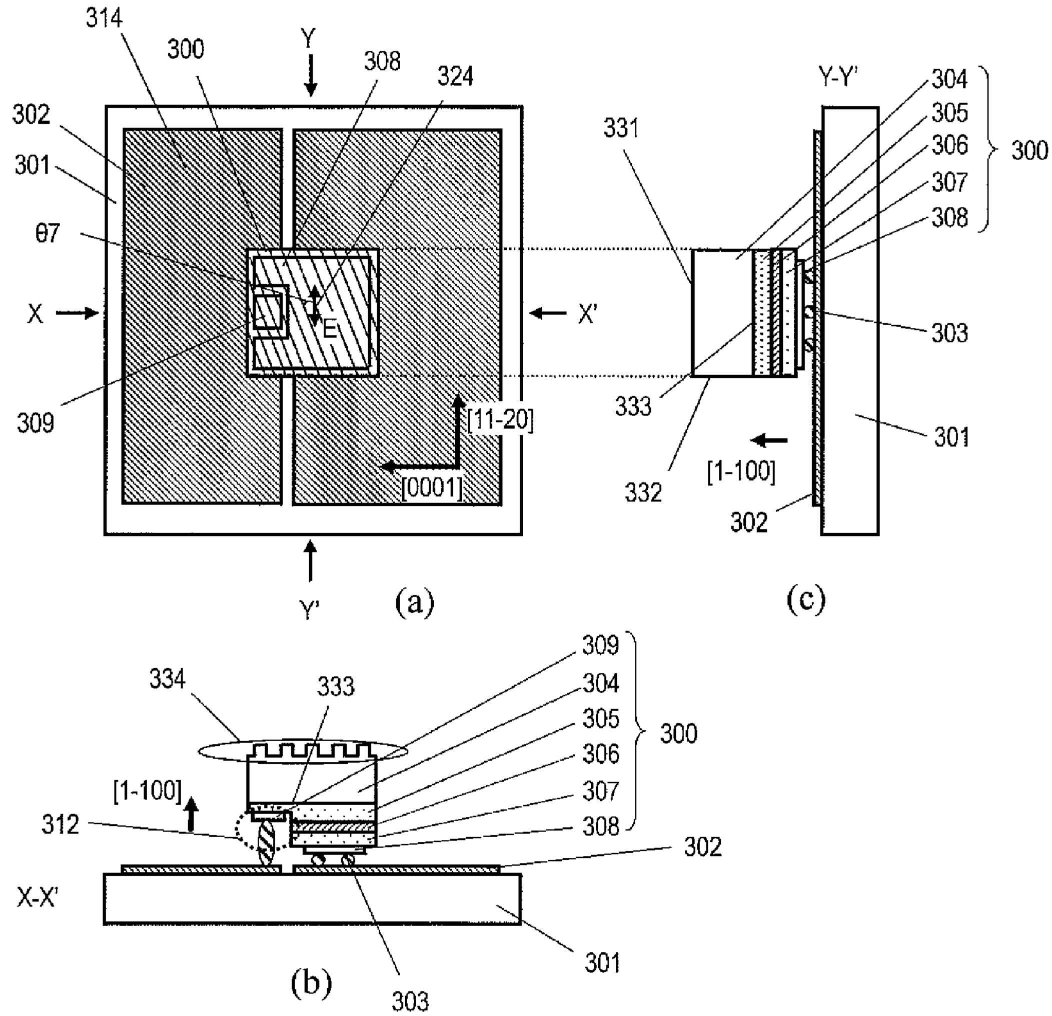

314
300
Y
308
324
302
301
θ2
E
θ2'
X'
[11-20]
X
[0001]
θ6
309
Y'
(a)
Y-Y'
304
305
306
300
332b
307
θ1
331
308
303
333
θ1
301
332d
[1-100]
302
(c)
309
304
331
333
300
332a
332c
305
[1-100]
θ1
306
θ1
307
312
308
302
X-X'
(b)
301
303

FIG.25



Y
302
314
300
308
324
301
θ2
E
θ2'
X
X'
[0001]
[11-20]
309
Y'
(a)
Y-Y'
304
305
306
307
308
300
331
332
333
θ1
303
332
θ1
301
[1-100]
302
(c)
334
309
304
333
332
332
305
300
[1-100]
θ1
θ1
306
312
307
308
302
X-X'
301
(b)
303
(d)
(e)
(f)
[0001]
[11-20]
θ7
E
X
X'
X-X'

FIG.26



314
300
Y
308
324
302
301
θ7
X
X'
E
309
[11-20]
[0001]
Y'
(a)
Y-Y'
304
305
306
307
308
300
331
303
333
301
[1-100]
332
302
(c)
309
304
305
306
307
308
300
334
333
[1-100]
312
302
X-X'
301
(b)
303

FIG.27

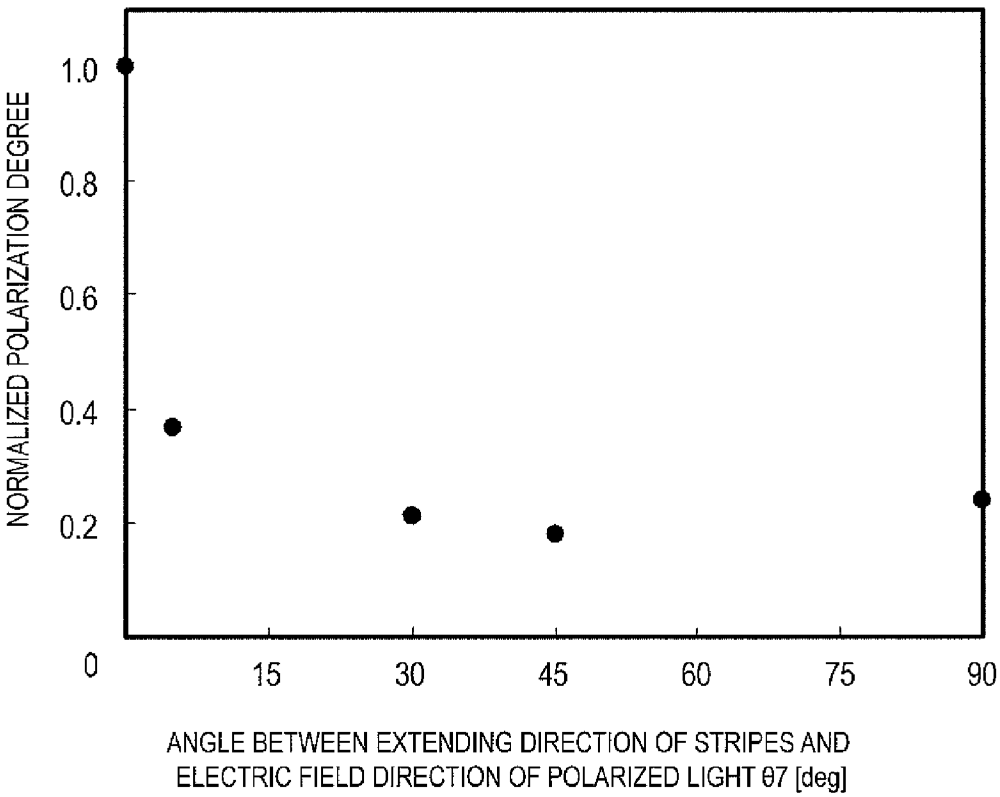

NORMALIZED POLARIZATION DEGREE
1.0
0.8
0.6
0.4
0.2
0
15
30
45
60
75
90
ANGLE BETWEEN EXTENDING DIRECTION OF STRIPES AND
ELECTRIC FIELD DIRECTION OF POLARIZED LIGHT θ7 [deg]

FIG.28

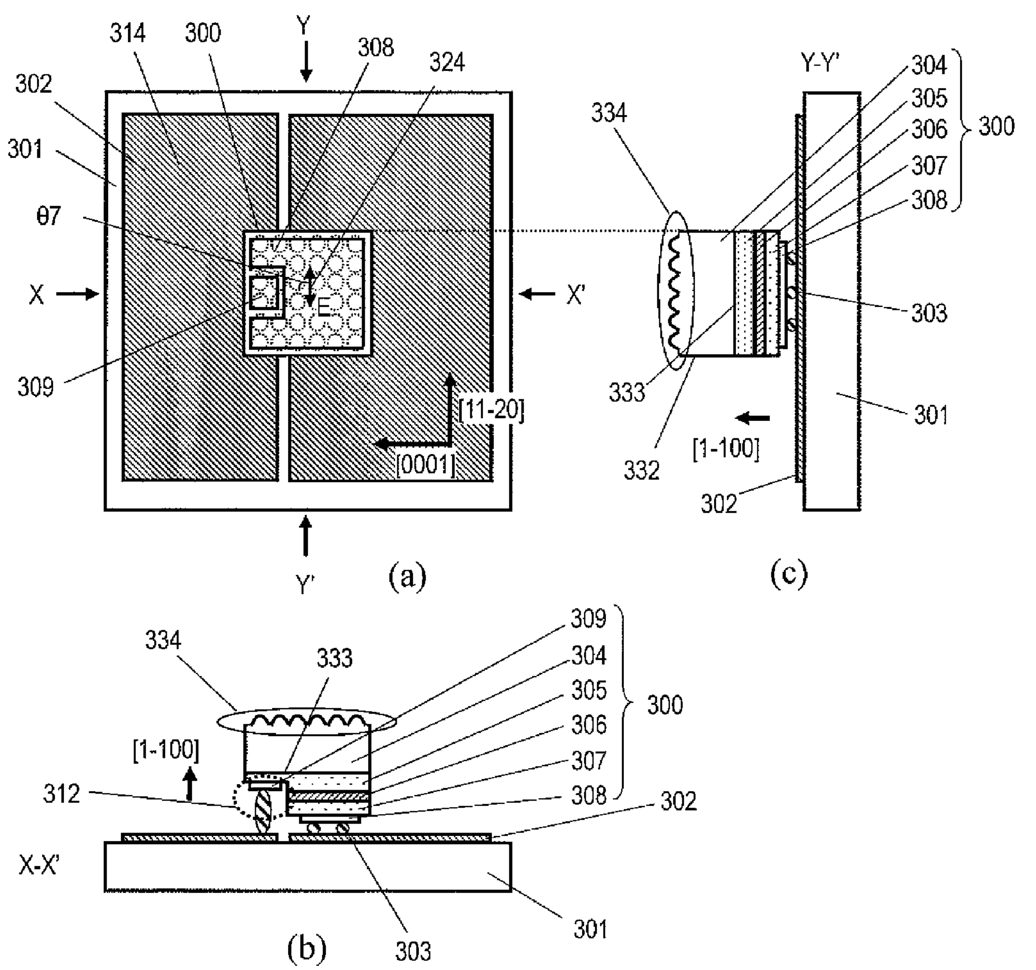
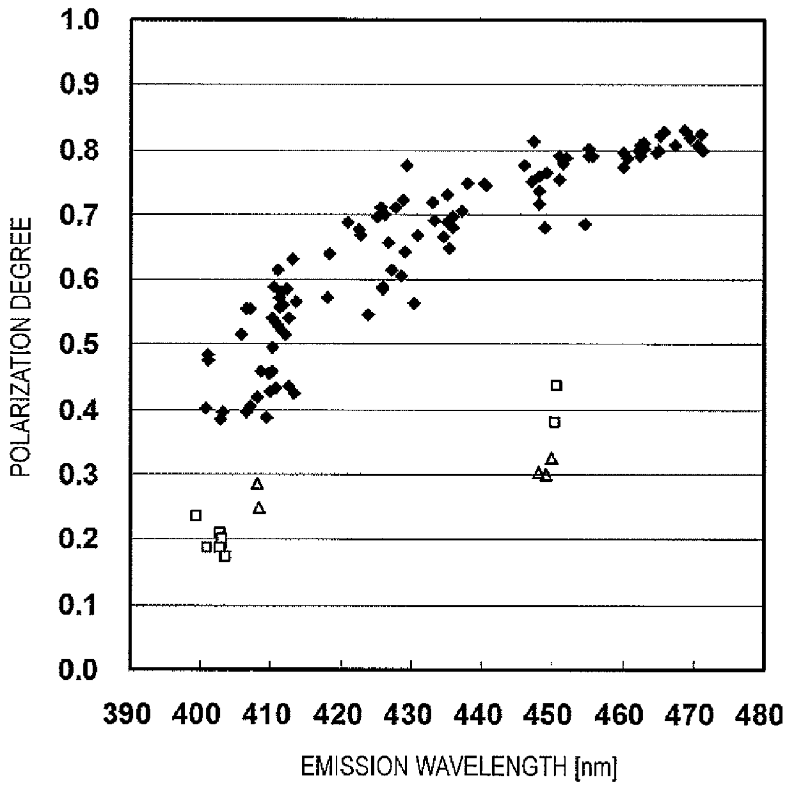

314
300
Y
308
324
302
301
θ7
X
X'
E
309
[11-20]
[0001]
Y'
(a)
Y-Y'
304
305
306
300
307
308
334
303
333
301
332
[1-100]
302
(c)
309
304
305
306
307
308
300
334
333
[1-100]
312
302
X-X'
301
(b)
303

FIG.29



◆: WITHOUT RECESSES AND ELEVATIONS ACROSS LIGHT EXTRACTION SURFACE 331
□: WITH RECESSES AND ELEVATIONS ACROSS LIGHT EXTRACTION SURFACE 331
△: WITH HEMISPHERICAL ELEVATED PORTIONS ACROSS LIGHT EXTRACTION SURFACE 331

FIG.30

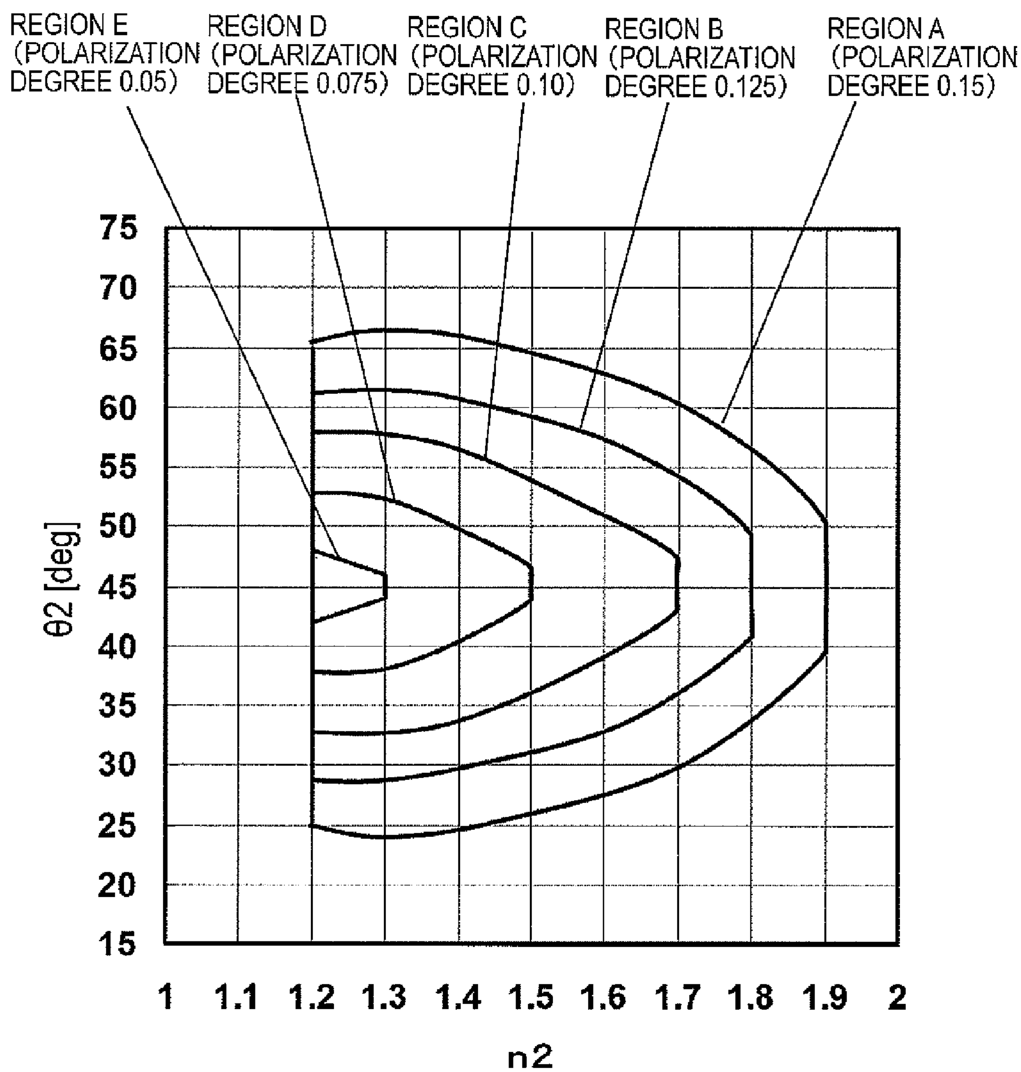

REGION E
(POLARIZATION
DEGREE 0.05)
REGION D
(POLARIZATION
DEGREE 0.075)
REGION C
(POLARIZATION
DEGREE 0.10)
REGION B
(POLARIZATION
DEGREE 0.125)
REGION A
(POLARIZATION
DEGREE 0.15)
75
70
65
60
55
50
45
40
35
30
25
20
15
θ2 [deg]
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
n2

FIG.31

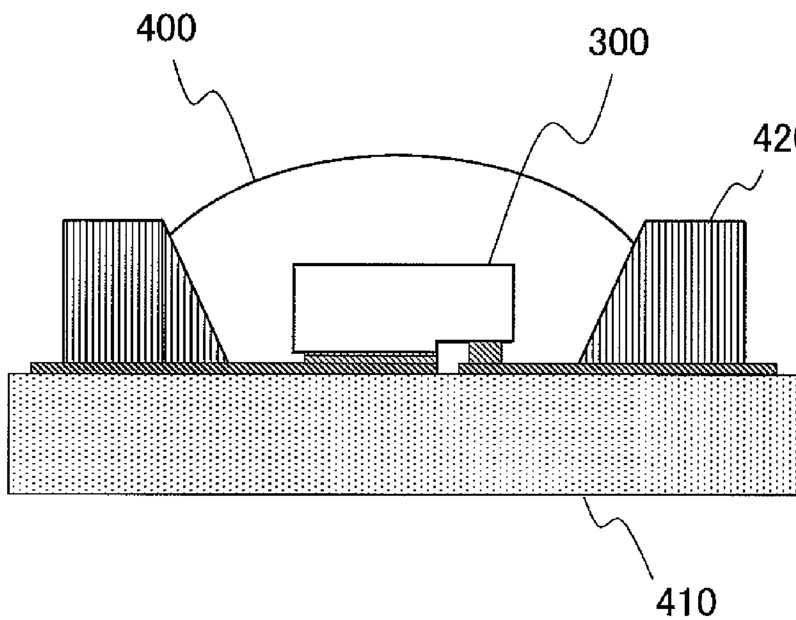
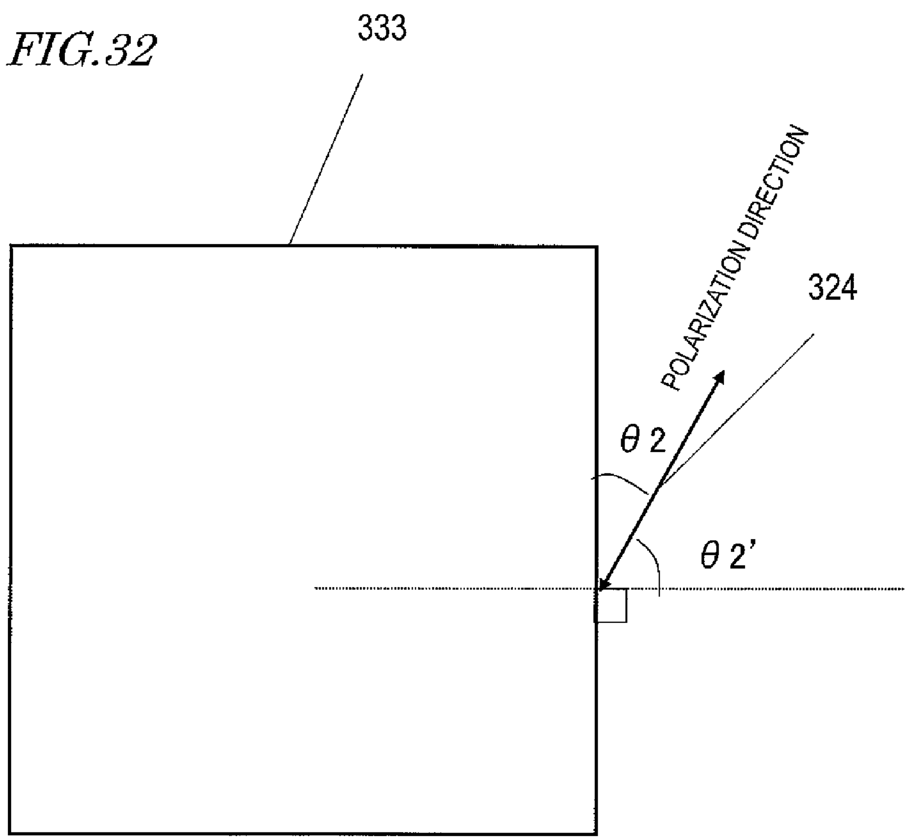


FIG.32



NITRIDE-BASED SEMICONDUCTOR LIGHT-EMITTING ELEMENT

This is a continuation of International Application No. PCT/JP2012/002385, with an international filing date of Apr. 5, 2012, which claims priority of Japanese Patent Application No. 2011-155684, filed on Jul. 14, 2011, the contents of which are hereby incorporated by reference.

BACKGROUND

1. Technical Field

The present application relates to a nitride-based semiconductor light-emitting element which includes a substrate which has a principal surface, a rear surface that is a light extraction surface, and a plurality of lateral surfaces, and a nitride semiconductor multilayer structure formed on the principal surface of the substrate. The present application also relates to a light source which includes a nitride-based semiconductor light-emitting element and to a method for manufacturing a nitride-based semiconductor light-emitting element.

2. Description of the Related Art

A nitride semiconductor containing nitrogen (N) as a Group V element is a prime candidate for a material to make a short-wave light-emitting device, because its bandgap is sufficiently wide. Among other things; gallium nitride-based compound semiconductors have been researched and developed particularly extensively. As a result, blue light-emitting diodes (LEDs), green LEDs, and blue semiconductor laser diodes in which gallium nitride-based compound semiconductors are used have already been used in actual products.

Hereinafter, the nitride semiconductors include a compound semiconductor in which some or all of gallium (Ga) atoms are replaced with at least one of aluminum (Al) and indium (In) atoms. Therefore, the nitride semiconductors are represented by formula $Al_xGa_yIn_zN$ ($0 \leq x, y, z \leq 1$, $x+y+z=1$).

By replacing Ga atoms with Al or In atoms, the bandgap can be greater than that of GaN. By replacing Ga atoms with In atoms, the bandgap can be smaller than that of GaN. This enables not only emission of short-wave light, such as blue light or green light, but also emission of orange light or red light. Because of such a feature, a nitride-based semiconductor light-emitting element has been expected to be applied to image display devices and lighting devices.

The nitride semiconductor has a wurtzite crystal structure. FIG. **1**A to FIG. **1**C show planes of a wurtzite crystal structure with four characters (hexagonal indices). In a four-character expression, crystal planes and orientations are expressed using primitive vectors of a**1**, a**2**, a**3**, and c. The primitive vector c runs in the [0001] direction, which is called a "c-axis". A plane that intersects with the c-axis at right angles is called either a "c-plane" or a "(0001) plane". FIG. **1**A shows c-plane as well as a-plane and m-plane. FIG. **1**B shows r-plane. FIG. **1**C shows (11-22) plane.

FIG. **2**A shows a molecular orbital model of the crystal structure of the nitride semiconductor. FIG. **2**B is a diagram showing an atomic arrangement near an m-plane surface, which is observed from the a-axis direction. The m-plane is perpendicular to the drawing sheet of FIG. **2**B. FIG. **2**C is a diagram showing an atomic arrangement at a +c-plane surface, which is observed from the m-axis direction. The c-plane is perpendicular to the drawing sheet of FIG. **2**C. As seen from FIG. **2**B, N atoms and Ga atoms reside at a plane which is parallel to the m-plane. On the other hand, as seen from FIG. **2**C, the c-plane includes layers in which only Ga atoms reside and layers in which only N atoms reside.

According to the conventional techniques, in fabricating a semiconductor element using nitride semiconductors, a c-plane substrate, i.e., a substrate which has a (0001)-plane principal surface, is used as a substrate on which nitride semiconductor crystals are to be grown. In this case, due to the arrangement of Ga atoms and N atoms, spontaneous electrical polarization is produced in the c-axis direction in the nitride semiconductor. That is why the c-plane is also called a "polar plane". As a result of the electrical polarization, a piezoelectric field is generated along the c-axis direction in the InGaN quantum well in the active layer of the nitride-based semiconductor light-emitting element. This electric field causes some positional deviation in the distributions of electrons and holes in the active layer, so that the internal quantum yield decreases due to the quantum confinement Stark effect of carriers.

Thus, it has been proposed that a substrate of which the principal surface is a so-called "non-polar plane", such as m-plane or a-plane, or a so-called "semi-polar plane", such as −r plane or (11-22) plane, be used. As shown in FIG. **1**, the m-planes in the wurtzite crystal structure are parallel to the c-axis and are six equivalent planes which intersect with the c-plane at right angles. For example, in FIG. **1**A, the (1-100) plane that is perpendicular to the [1-100] direction is the m-plane. The other m-planes which are equivalent to the (1-100) plane include (−1010) plane, (10-10) plane, (−1100) plane, (01-10) plane, and (0-110) plane. Here, "−" attached on the left-hand side of a Miller-Bravais index in the parentheses means a "bar", which conveniently represents inversion of that index.

On the m-plane, as shown in FIG. **2**(*b*), Ga atoms and N atoms are on the same atomic-plane. For that reason, no electrical polarization will be produced perpendicularly to the m-plane. Therefore, if a light-emitting element is fabricated using a semiconductor multilayer structure which has been formed on the m-plane, no piezoelectric field will be generated in the active layer, thus overcoming the problem that the internal quantum yield is decreased due to the quantum confinement Stark effect of carriers. This also applies to the a-plane that is one of the other non-polar planes than the m-plane. Also, similar effects can be achieved even in the case of a so-called semi-polar plane, such as −r plane or (11-22) plane.

Further, a nitride-based semiconductor light-emitting element including an active layer which is formed on the m-plane, the a-plane, the −r plane or the (11-22) plane has a polarization characteristic which is attributed to the structure of its valence band.

For example, Japanese Laid-Open Patent Publication No. 2009-71174 (hereinafter, referred to as "Patent Document 1") discloses, as a method for improving the polarization characteristic of a nitride-based semiconductor light-emitting element whose principal surface is a non-polar plane or a semi-polar plane, separating nitride-based semiconductor light-emitting elements into small chips each having a rhombic shape or a triangular shape, so that a resultant configuration prevents decrease of the polarization degree of light outgoing from a lateral surface of the nitride-based semiconductor light-emitting element.

For example, Japanese Laid-Open Patent Publication No. 2007-234908 (hereinafter, referred to as "Patent Document 2") discloses, as a method for improving the reliability of a nitride-based semiconductor light-emitting element, isolating M-plane or R-plane nitride-based semiconductor light-emitting elements into nitride semiconductor chips in such a manner that the isolation is carried out with an inclination of 30 to 60 degrees with respect to a cleavage surface.

For example, Japanese Laid-Open Patent Publication No. 2008-277323 (hereinafter, referred to as "Patent Document 3") discloses, as a method for improving light extraction from a nitride-based semiconductor light-emitting element having an a-plane principal surface, isolating nitride semiconductor chips in such a manner that the isolation is carried out with an inclination of 5 to 85 degrees with respect to a cleavage surface. This leads to generation of recesses and elevations across a lateral surface of the nitride semiconductor chip, so that light extraction from the lateral surface improves.

SUMMARY

In the above-described conventional techniques, further improvement of the light emission quality has been demanded.

One of the major objects of the present invention is to provide a nitride-based semiconductor light-emitting device having improved light emission quality.

A nitride-based semiconductor light-emitting element of one embodiment is a nitride-based semiconductor light-emitting element which includes a substrate which has a principal surface, a rear surface that is a light extraction surface, and a plurality of lateral surfaces, and a nitride semiconductor multilayer structure formed on the principal surface of the substrate, wherein the nitride semiconductor multilayer structure includes an active layer which emits polarized light, angle θ is greater than 90°, and angle θ**2** (mod 180°) is an angle which does not include 0° or 90°, where the angle θ is an angle which is formed by at least one of the plurality of lateral surfaces of the substrate with respect to the principal surface of the substrate, and the angle θ**2** is an absolute value of an angle which is formed by an intersecting line of at least one of the plurality of lateral surfaces of the substrate and the principal surface of the substrate with respect to a polarization direction in the principal surface of the polarized light.

According to the above aspect, θ is greater than 90°, and θ**2** is an angle which does not include 0° or 90°. Therefore, part of polarized light emitted from a nitride semiconductor active layer is converted to elliptical polarization and reflected at a lateral surface of a substrate and then can be extracted from the rear surface. As a result, the polarization degree can be reduced, and the emission quality can be improved.

These general and specific aspects may be implemented using a system, a method and any combination of systems and methods.

Additional benefits and advantages of the disclosed embodiments will be apparent from the specification and Figures. The benefits and/or advantages may be individually provided by the various embodiments and features of the specification and drawings disclosure, and need not all be provided in order to obtain one or more of the same.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a diagram showing a c-plane, an a-plane, and an m-plane of a wurtzite crystal structure.

FIG. **1**B is a diagram showing an r-plane of wurtzite crystal structure.

FIG. **1**C is a diagram showing a (11-22) plane of a wurtzite crystal structure.

FIG. **2**A is a diagram showing the crystal structure of a nitride semiconductor using a molecular orbital model.

FIG. **2**B is a diagram showing an atomic arrangement near an m-plane surface, which is observed from the a-axis direction.

FIG. **2**C is a diagram showing an atomic arrangement near a +c plane surface, which is observed from the m-axis direction.

FIGS. **3**(*a*) to **3**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element having an m-plane principal surface.

FIG. **4** is a graph showing measurement results of the emission wavelength and the polarization degree of a nitride-based semiconductor light-emitting element having an m-plane principal surface.

FIG. **5** is a diagram for illustrating a method for measuring the polarization degree.

FIGS. **6**(*a*) to **6**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of Embodiment 1.

FIGS. **7**A to **7**C are diagrams for illustrating the principle of reducing the polarization degree in Embodiment 1.

FIG. **8**A is a diagram showing the types of polarization.

FIGS. **8**B and **8**C are graphs showing calculation results of the polarization ellipticity and the polarization degree in the case where one lateral surface **332** in Embodiment 1 is considered.

FIGS. **9**A and **9**B are graphs showing calculation results of the critical angle and the relative phase difference in the case where one lateral surface **332** in Embodiment 1 is considered.

FIG. **10**A is a graph showing the proportion (calculation result) of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from a light extraction surface **331**.

FIG. **10**B is a graph where values are plotted at which the proportion of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from the light extraction surface **331** is 70% in the graph of FIG. **10**A.

FIG. **11** is a graph showing calculation results of the polarization degree in the case where four lateral surfaces **332** in Embodiment 1 are considered.

FIG. **12**A is a graph showing results of calculation of how the proportion of light which is extracted from the light extraction surface **331** to the outside with its polarization being maintained depends on D/L**1** and n**2**.

FIG. **12**B is a graph showing results of calculation of the relationship between n**2** and D/L**1** for values of the area occupation ratio R.

FIG. **13** is a graph showing measurement results of the electric current density and the external quantum efficiency EQE of a nitride-based semiconductor light-emitting element whose principal surface is a c-plane and a nitride-based semiconductor light-emitting element whose principal surface is an m-plane.

FIG. **14**A is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.9.

FIG. **14**B is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.8.

FIG. **14**C is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.7.

FIG. **14**D is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.6.

FIG. **14**E is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.5.

FIG. **14**F is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.4.

FIG. **14**G is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.3.

FIG. **14**H is a graph showing calculation results of the polarization degree in the case where all of the light extraction surfaces in Embodiment 1 are considered and the refractive index n**2** is 1.2.

FIG. **15** is a graph showing appropriate ranges of θ**2** and n**2** in the case where all of the light extraction surfaces in Embodiment 1 are considered.

FIGS. **16**(*a*) and **16**(*b*) are diagrams for illustrating a manufacturing method of Embodiment 1 in which laser dicing is employed.

FIGS. **17**(*a*) and **17**(*b*) are diagrams for illustrating another manufacturing method of Embodiment 1 in which blade dicing is employed.

FIGS. **18**A and **18**B show a photographic image of the top surface and a cross-sectional profile of a nitride-based semiconductor light-emitting element which was separated into a small chip by means of blade dicing.

FIGS. **19**(*a*) to **19**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of the first variation of Embodiment 1.

FIGS. **20**(*a*) to **20**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of the second variation of Embodiment 1.

FIGS. **21**(*a*) to **21**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of the third variation of Embodiment 1.

FIGS. **22**(*a*) to **22**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of Embodiment 2.

FIGS. **23**(*a*) to **23**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of Embodiment 3.

FIGS. **24**(*a*) to **24**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element of the first variation of Embodiment 3.

FIGS. **25**(*a*) to **25**(*f*) are diagrams showing a nitride-based semiconductor light-emitting element of Embodiment 4.

FIGS. **26**(*a*) to **26**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element having an m-plane principal surface, in which a light extraction surface **331** has striped recesses and elevations.

FIG. **27** is a graph showing measurement results of the polarization degree in the case where a light extraction surface **331** of a nitride-based semiconductor light-emitting element having an m-plane principal surface has striped recesses and elevations.

FIGS. **28**(*a*) to **28**(*c*) are diagrams showing a nitride-based semiconductor light-emitting element having an m-plane principal surface in which the light extraction surface **331** has recesses and elevations which have a shape approximate to a hemisphere.

FIG. **29** is a graph of measurement results which illustrates the effect of reducing the polarization degree in the case where the light extraction surface **331** has recesses and elevations.

FIG. **30** is a graph showing appropriate ranges of θ**2** and n**2** in the case where all of the light extraction surfaces in Embodiment 4 are considered.

FIG. **31** is a schematic diagram showing an example of a white light source which includes a nitride-based semiconductor light-emitting element **300** of an embodiment.

FIG. **32** is a diagram for illustrating θ**2**.

DETAILED DESCRIPTION

One embodiment of the present invention is a nitride-based semiconductor light-emitting element including a substrate which has a principal surface, a rear surface that is a light extraction surface, and a plurality of lateral surfaces, and a nitride semiconductor multilayer structure formed on the principal surface of the substrate, wherein the nitride semiconductor multilayer structure includes an active layer which emits polarized light, angle θ is greater than 90°, and angle θ**2** (mod 180°) is an angle which does not include 0° or 90°, where the angle θ is an angle which is formed by at least one of the plurality of lateral surfaces of the substrate with respect to the principal surface of the substrate, and the angle θ**2** is an absolute value of an angle which is formed by an intersecting line of at least one of the plurality of lateral surfaces of the substrate and the principal surface of the substrate with respect to a polarization direction in the principal surface of the polarized light.

The above configuration enables reduction of the polarization degree and improvement of the emission quality.

The substrate may be an off-cut substrate of not more than 5°.

A value of (θ−90°) may be not less than a value of the angle θ**1** which satisfies Formula 9:

$$\theta 1 = 51.0 - 21.5 \times n2 \quad \text{(Formula 9)}$$

The value of (θ−90°) may be greater than critical angle θc which is determined by refractive indices n**1** and n**2**, where n**1** is a refractive index for light of the substrate and n**2** is a refractive index of a medium which is in contact with the plurality of lateral surfaces of the substrate.

A planar shape of the principal surface and the rear surface of the substrate may be a quadrangular shape, and the plurality of lateral surfaces may be four lateral surfaces.

A planar shape of the principal surface and the rear surface of the substrate may be any of a parallelogrammatic shape, a square shape, a rectangular shape, and a rhombic shape.

The angle θ**2** (mod 90°) may be not less than 25° and not more than 65°, may be not less than 35° and not more than 55°, or may be not less than 40° and not more than 50°.

The rear surface of the substrate may have a plurality of elevated portions.

The elevated portions may have a conical shape or a hemispherical shape and may be two-dimensionally arranged across the rear surface of the substrate.

The elevated portions may have a striped shape, and γ (mod 180°) may be not less than 5° and not more than 175° or may be not less than 30° and not more than 150° where γ is an absolute value of an angle which is formed between an extending direction of the striped shape and a polarization direction of the polarized light.

σ1 (mod 180°) may be not less than 85° and not more than 95° where σ1 is an absolute value of an angle which is formed between a polarization direction of the polarized light and a normal line of the principal surface of the substrate, and σ2 (mod 180°) may be not less than 85° and not more than 95° where σ2 is an absolute value of an angle which is formed between the polarization direction of the polarized light and a normal line of the rear surface of the substrate.

A light source of one embodiment of the present invention includes a nitride-based semiconductor light-emitting element of one embodiment and a wavelength converter including a phosphor that converts at least a wavelength of light emitted from the rear surface of the substrate.

A nitride-based semiconductor element manufacturing method of one embodiment of the present invention is a nitride-based semiconductor element manufacturing method including the steps of: (a) providing a substrate which has a principal surface and a rear surface that is a light extraction surface; (b) forming a nitride semiconductor multilayer structure on the principal surface of the substrate; and (c) cutting the substrate and the nitride semiconductor multilayer structure into a plurality of nitride-based semiconductor elements, wherein the nitride semiconductor multilayer structure includes an active layer which emits polarized light, and step (c) includes cutting the substrate and the nitride semiconductor multilayer structure such that angle θ is greater than 90°, and angle $\theta 2$ is an angle which does not include 0° or 90°, where the angle θ is an angle which is formed by at least one of the plurality of lateral surfaces of the substrate with respect to the principal surface of the substrate and the angle $\theta 2$ is an absolute value of an angle which is formed by an intersecting line of at least one of the plurality of lateral surfaces of the substrate and the principal surface of the substrate with respect to a polarization direction in the principal surface of the polarized light.

The substrate provided in step (a) may be an off-cut substrate of not more than 5°.

A value of $(\theta-90°)$ may be not less than a value of the angle $\theta 1$ which satisfies Formula 9:

$$\theta 1=51.0-21.5\times n2 \qquad \text{(Formula 9)}$$

$\sigma 1$ (mod 180°) may be not less than 85° and not more than 95° where $\sigma 1$ is an absolute value of an angle which is formed between a polarization direction of the polarized light and a normal line of the principal surface of the substrate, and $\sigma 2$ (mod 180°) may be not less than 85° and not more than 95° where $\sigma 2$ is an absolute value of an angle which is formed between the polarization direction of the polarized light and a normal line of the rear surface of the substrate.

Next, one considered aspect of the present embodiment is discussed. A nitride-based semiconductor light-emitting element including an active layer which is formed on the m-plane, a-plane, −r plane or (11-22) plane has a polarization characteristic which is attributed to the structure of its valence band. FIGS. **3**(*a*) to **3**(*c*) show an example of a nitride-based semiconductor light-emitting element manufactured on a substrate **304** which includes an en-plane GaN layer at its surface. FIG. **3**(*a*) is a top view. FIG. **3**(*b*) is a cross-sectional view taken along line X-X' of FIG. **3**(*a*). FIG. **3**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **3**(*a*). The nitride-based semiconductor light-emitting element **300** includes a n-type nitride semiconductor layer **305** provided on the substrate **304**, a nitride semiconductor active layer **306**, a p-type nitride semiconductor layer **307**, a p-side electrode **308** which is provided so as to be in contact with the p-type nitride semiconductor layer **307**, and a n-side electrode **309** which is provided so as to be in contact with the n-type nitride semiconductor layer **305**. A surface of a mounting base **301** is provided with a wire **302**. The nitride-based semiconductor light-emitting element **300** and the wire **302** provided on the mounting base **301** are connected to each other via a bump **303**. Light emitted from the nitride semiconductor active layer **306** is extracted from a light extraction surface **331** and four lateral surfaces **332** to the outside. Each lateral surface **332** is parallel to the c-plane or the a-plane of a nitride semiconductor crystal. Such a nitride semiconductor active layer formed on the m-plane mainly emits light whose electric field intensity is deviated in a direction parallel to the a-axis. A light-emitting element which has such a polarization characteristic is suitable when applied to a backlight for a liquid crystal display device, for example. However, when applied to decorative illumination or lighting purposes, the amount of reflection of light varies depending on the installation orientation. Therefore, the quality of the light-emitting element, when employed in such fields, deteriorates.

In this specification, light whose electric field intensity is deviated in a specific direction is referred to as "polarized light". For example, light whose electric field intensity is deviated in a direction parallel to X-axis is referred to as "X-axis direction polarized light". The direction parallel to the X-axis on this assumption is referred to as "polarization direction". Note that the "X-axis direction polarized light" not only means linearly-polarized light which is polarized in the X-axis direction but may include linearly-polarized light which is polarized in a different direction. More specifically, the "X-axis direction polarized light" means light in which the intensity (electric field intensity) of light transmitted through a "polarizer which has a polarization transmission axis extending in the X-axis direction" is higher than the electric field intensity of light transmitted through a polarizer which has a polarization transmission axis extending in a different direction. Therefore, the "X-axis direction polarized light" includes not only linearly-polarized light and elliptically-polarized light which are polarized in the X-axis direction but also a wide variety of non-coherent light in which linearly-polarized light and elliptically-polarized light which are polarized in various directions are mixed together.

The "polarization direction in a plane" refers to a direction resulting from projection of the polarization direction onto the plane.

While rotating the polarization transmission axis of the polarizer around the optical axis, the electric field intensity of light transmitted through the polarizer exhibits the strongest intensity, Imax, and the weakest intensity, Imin. The polarization degree is defined by the following formula:

$$|I\text{max}-I\text{min}|/|I\text{max}+I\text{min}|$$

In the case of the "X-axis direction polarized light", when the polarization transmission axis of the polarizer is parallel to the X-axis, the electric field intensity of the light transmitted through the polarizer is Imax. When the polarization transmission axis of the polarizer is parallel to the Y-axis, the electric field intensity of the light transmitted through the polarizer is Imin. In the case of perfectly linearly-polarized light, Imin=0, and therefore, the polarization degree is equal to 1. On the other hand, in the case of perfectly unpolarized light, Imax−Imin=0, and therefore, the polarization degree is equal to 0.

A nitride semiconductor light-emitting element which includes an active layer formed on the m-plane mainly emits the a-axis direction polarized light as described above. Meanwhile, it also emits the c-axis direction polarized light and the m-axis direction polarized light. However, the c-axis direction polarized light and the m-axis direction polarized light have weaker intensities than the a-axis direction polarized light.

The present inventors manufactured a nitride-based semiconductor light-emitting element including an active layer which was formed on the m-plane such as shown in FIG. **3**. FIG. **4** is a graph showing measurement results of the emission wavelength and the polarization degree of the manufactured nitride-based semiconductor light-emitting element. The nitride semiconductor active layer **306** is made of InGaN. The emission wavelength is controlled by changing the mole fraction of In. The measurement of the polarization degree was carried out using an optical system shown in FIG. **5**. Specifically, a LED **1** is powered by a power supply **6** to emit light. The emission of the LED **1** is checked using a stereoscopic microscope **3**. The stereoscopic microscope **3** has two ports. A silicon photodetector **4** is attached to one of the ports, and a CCD camera is attached to the other. A polarizing plate **2** is provided between the stereoscopic microscope **3** and the LED **1**. While rotating the polarizing plate **2**, the maximum and the minimum of the emission intensity are measured using the silicon photodetector **4**. As seen from FIG. **4**, the configuration of FIG. **3** exhibits a polarization degree of about 0.3 to 0.8 depending on the emission wavelength. Since the polarization degree is greater than 0.1, it is difficult to employ the nitride-based semiconductor light-emitting element shown in FIG. **3** in existing applications without modification.

Patent Document 1 intends to maintain the polarization characteristic of a nitride-based semiconductor light-emitting element. However, when a light-emitting element which has a polarization characteristic is used as a light source, the amount of reflection at an object surface varies depending on the orientation of the polarization, i.e., the installation orientation of the LED, leading to a problem that the appearance of the object varies. This is because the P-polarized light and the S-polarized light exhibit different reflectances (the S-polarization has higher reflectance at the object surface). Here, the P-polarized light refers to light which has an electric field component that is parallel to the incidence plane. The S-polarized light refers to light which has an electric field component that is perpendicular to the incidence plane. In an application which utilizes the polarization characteristic without modification, improving the polarization degree is important. In common lighting applications, there is a problem that the polarization characteristic is a troublesome factor. Also, in Patent Document 1, the angle which is formed between a lateral surface and the principal surface of a separated semiconductor chip is not clearly disclosed.

Patent Document 2 intends to improve the reliability of a nitride-based semiconductor light-emitting element. In Patent Document 2, there is no description of the polarization degree, and the relationship between the cleaving direction and the polarization degree is indefinite. Also, in Patent Document 2, the angle which is formed between a lateral surface and the principal surface of a separated semiconductor chip is not clearly disclosed.

Patent Document 3 intends to improve light extraction from a nitride-based semiconductor light-emitting element. Therefore, in Patent Document 3, there is no description of the polarization degree, and the relationship between the cleaving direction and the polarization degree is indefinite. Also, in Patent Document 3, the angle which is formed between a lateral surface and the principal surface of a separated semiconductor chip is not clearly disclosed.

The present inventors conducted detailed research on the dependence of a polarization degree of polarized light emitted from a nitride-based semiconductor light-emitting element which is achieved in the case where the polarized light is transmitted through a lateral surface of the nitride-based semiconductor light-emitting element to the outside on the shape of the nitride-based semiconductor light-emitting element, and the dependence of a polarization degree of polarized light emitted from a nitride-based semiconductor light-emitting element which is achieved in the case where the polarized light is reflected at a lateral surface of the nitride-based semiconductor light-emitting element before being transmitted to the outside on the shape of the nitride-based semiconductor light-emitting element. Part of the polarized light is reflected at the interface between the lateral surface of the nitride-based semiconductor light-emitting element and the outside, while the remaining part is transmitted through the interface. As a result of the research conducted by the present inventors, it was discovered that these transmittance and reflectance depend on the polarization direction of the polarized light generated in the active layer of the nitride-based semiconductor light-emitting element and the shape of the lateral surface of the nitride-based semiconductor light-emitting element. Based on this discovery, the shape of the nitride-based semiconductor light-emitting element which enables reduction of the polarization degree of light radiated from the nitride-based semiconductor light-emitting element was conceived.

Hereinafter, embodiments of the present invention will be described with reference to the drawings. In the drawings mentioned below, for the sake of simple description, elements which perform substantially the same functions are denoted by the same reference numerals. Note that the present invention is not limited to the embodiments which will be described below.

Embodiment 1

The first embodiment is described with reference to FIG. **6**.

Firstly, refer to FIGS. **6**(*a*) to **6**(*c*). FIG. **6**(*a*) is a top view schematically showing a nitride-based semiconductor light-emitting device of the present embodiment. FIG. **6**(*b*) is a cross-sectional view taken along line X-X' of FIG. **6**(*a*). FIG. **6**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **6**(*a*).

A nitride-based semiconductor light-emitting element **300** of the present embodiment includes a substrate **304** which has a principal surface **333**, a rear surface that is a light extraction surface **331**, and a plurality of lateral surfaces **332**, and a nitride semiconductor multilayer structure which is provided on the principal surface **333** of the substrate **304** and which includes a nitride semiconductor active layer **306** that emits polarized light.

Here, an angle which is formed by the plurality of lateral surfaces **332** of the substrate **304** with respect to the principal surface **333** of the substrate **304** is referred to as angle θ. In commonly-employed elements, the lateral surfaces of a substrate are perpendicular to the principal surface and the rear surface of the substrate, and the angle θ is 90°. In the present embodiment, the lateral surfaces **332** of the substrate **304** are inclined with respect to the vertical direction of the principal surface **333** and the light extraction surface **331** of the substrate **304**. The lateral surfaces **332** are inclined such that the lateral surfaces **332** extend outward in a direction from the principal surface **333** to the light extraction surface **331** of the substrate **304**. Therefore, the angle θ is greater than 90°.

In the present embodiment, the sides that constitute the perimeter of the principal surface **333** of the substrate **304** are inclined with respect to the a-axis direction (polarization direction **324**). The sides that constitute the perimeter of the principal surface **333** of the substrate **304** can be rephrased as "the intersecting lines of the plurality of lateral surfaces **332** of the substrate **304** and the principal surface **333** of the substrate **304**". Where the absolute value of an angle which is formed by the intersecting lines with respect to the polarization direction **324** in the principal surface **333** of polarized light (a-axis direction) is referred to as angle θ2, the angle θ2 (mod) 180° is an angle which does not include 0° or 90°. Here, "mod 180°" refers to an angle of the reminder resulting from division of that angle by 180°.

According to the present embodiment, the lateral surfaces **332** of the substrate **304** are inclined with respect to the vertical direction of the principal surface **333** and the light extraction surface (rear surface) **331** of the substrate **304**, and therefore, the proportion of reflection at the lateral surfaces **332** of the light emitted from the nitride semiconductor active layer **306** can be increased. Due to the Goos-Hanchen shift, a phase difference occurs in the light reflected at the lateral surfaces **332**, and the light reflected at the lateral surfaces **332** is converted to elliptical polarization. This phase difference occurs depending on the refractive index of the substrate, n**1**, and the refractive index of a portion surrounding the substrate, n**2**. The light reflected at the lateral surfaces **332** outgoes from the principal surface **333** to the outside, for example. According to the present embodiment, light from the nitride semiconductor active layer **306** can be converted to elliptical polarization, and therefore, the polarization degree is reduced, and the quality of emission can be improved. Details of the effects will be described later using calculation results.

The specific structure of the nitride-based semiconductor light-emitting element **300** of the present embodiment is not particularly limited, so long as it includes an element which has a polarization characteristic. The nitride-based semiconductor light-emitting element **300** includes, for example, a substrate **304** which includes at least an m-plane GaN layer, a n-type nitride semiconductor layer **305** which is formed on the m-plane GaN layer, a nitride semiconductor active layer **306**, a p-type nitride semiconductor layer **307**, a p-side electrode **308** which is provided so as to be in contact with the p-type nitride semiconductor layer **307**, and a n-side electrode **309** which is provided so as to be in contact with the n-type nitride semiconductor layer **305**. Here, the nitride semiconductor may be an $Al_xIn_yGa_zN$ (x+y+z=1, x≥0, y≥0, z≥0) semiconductor or may be a GaN-based semiconductor ($Al_xIn_yGa_zN$ (x+y+z=1, x≥0, y≥0, z>0).

In this specification, the non-polar plane, "a-plane", "r-plane", "−r plane", "(11-22) plane", and "m-plane" include not only planes which are perfectly parallel to the non-polar plane, a-plane, r-plane, −r plane, "(11-22) plane", and m-plane but also planes which are inclined (off-cut) by an angle of ±5° or less with respect to the non-polar plane, a-plane, r-plane, −r plane, "(11-22) plane", and m-plane. That is, the substrate **304** may be an off-cut substrate (off substrate) which is inclined by an angle of 5° or less. With just a slight incline with respect to the m-plane, the effect of a variation of the spontaneous electrical polarization is very small. On the other hand, according to the crystal growth technology, epitaxial growth of a semiconductor layer is easier on a substrate in which the crystal orientation is slightly inclined rather than on a substrate in which the crystal orientation is strictly identical. Thus, in some cases, it may be beneficial to incline the crystal plane for the purpose of improving the quality of a semiconductor layer which is to be epitaxially grown or increasing the crystal growth rate, while sufficiently decreasing the effect of the spontaneous electrical polarization.

If the inclination angle is large, the polarization direction varies depending on whether it is off in the a-axis direction or off in the c-axis direction. However, if it is off by about ±5°, a direction in which the electric field intensity is the strongest is identical with the a-axis direction. In this case, the "polarization direction in the principal surface" refers to a direction resulting from projection of the a-axis direction onto the principal surface.

The substrate **304** may be an m-plane GaN substrate or may be an m-plane SiC substrate which includes an m-plane GaN layer in its surface or a r-plane or m-plane sapphire substrate which includes an m-plane GaN layer in its surface. The most important aspect is that light emitted from the active layer is polarized in a specific direction.

In the case where the substrate **304** is an m-plane GaN substrate, in consideration of the above-described inclination, σ1 (mod 180°) is not less than 85° and not more than 95° (where σ1 is the absolute value of an angle which is formed between the polarization direction of polarized light and the normal line of the principal surface of the substrate **304**), and σ2 (mod 180°) is not less than 85° and not more than 95° (where σ2 is the absolute value of an angle which is formed between the polarization direction of polarized light and the normal line of the rear surface of the substrate **304**).

The plane orientation of the nitride semiconductor active layer is not limited to the m-plane but only needs to be a non-polar plane or a semi-polar plane. An example of the non-polar plane is a-plane. Examples of the semi-polar plane include −r plane and (11-22) plane. As previously described, a nitride semiconductor active layer formed on the m-plane mainly emits light whose electric field intensity is deviated in a direction parallel to the a-axis. A nitride semiconductor active layer formed on the a-plane mainly emits light whose electric field intensity is deviated in a direction parallel to the m-axis. A nitride semiconductor active layer formed on the (11-22) plane, which is a semi-polar plane, mainly emits light whose electric field intensity is deviated in a direction parallel to the m-axis when the mole fraction of In in the nitride semiconductor active layer is small. However, the nitride semiconductor active layer formed on the (11-22) plane mainly emits light whose electric field intensity is deviated in a direction parallel to the [−1-123] direction, when the mole fraction of In in the nitride semiconductor active layer is large. The polarization characteristic of the nitride semiconductor active layer **306** provided on such a semi-polar plane depends on the behaviors of the upper two of the valence bands (A band and B band) and varies according to the amount of strain imposed on the nitride semiconductor active layer **306** or the quantum confinement effect in some cases.

For example, in the case where a substrate which is off-cut by 5° with respect to the m-plane is used, the nitride semiconductor active layer **306** also has a plane orientation which is inclined by 5° with respect to the m-plane. When the off-cut angle with respect to the m-plane is small as described herein, the nitride semiconductor active layer **306** mainly emits light whose electric field intensity is deviated in a direction parallel to the a-axis.

In the present embodiment, the principal surface of the substrate refers to a substrate surface on which the semiconductor multilayer structure is to be formed. The principal surface of each nitride semiconductor layer refers to a surface of the growing direction of each nitride semiconductor layer (growing surface). These principal surfaces are generally parallel to one another. Hereinafter, a surface which is simply referred to as "principal surface" without a reference mark means "the principal surface of the substrate or the nitride semiconductor active layer".

An undoped GaN layer may be provided between the nitride semiconductor active layer **306** and the p-type nitride semiconductor layer **307**.

The n-type nitride semiconductor layer **305** is made of, for example, n-type $Al_uGa_vIn_wN$ (u+v+w=1, u≥0, v≥0, w≥0).

The n-type dopant used may be, for example, silicon (Si). The p-type nitride semiconductor layer **307** is made of, for example, a p-type Al_sGa_tN (s+t=1, s≥0, t≥0) semiconductor. As the p-type dopant, for example, Mg is added. Examples of the p-type dopant other than Mg include Zn and Be. In the p-type nitride semiconductor layer **307**, the mole fraction of Al, s, may be uniform along the thickness direction. Alternatively, the Al mole fraction s may vary either continuously or stepwise along the thickness direction. Specifically, the thickness of the p-type nitride semiconductor layer **307** is, for example, about not less than 0.05 μm and not more than 2 μm.

Part of the p-type nitride semiconductor layer **307** near the upper surface, i.e., near the interface with the p-side electrode **308**, may be made of a semiconductor whose Al mole fraction s is zero, i.e., GaN. Also, in this case, the GaN contains a p-type impurity with high concentration and is capable of functioning as a contact layer.

The nitride semiconductor active layer **306** has a GaInN/GaInN multi-quantum well (MQW) structure in which, for example, $Ga_{1-x}In_xN$ well layers, each having a thickness of about not less than 3 nm and not more than 20 nm, and $Ga_{1-y}In_yN$ well layers ($0 \leq y < x < 1$) barrier layers, each having a thickness of about not less than 5 nm and not more than 30 nm, are alternately stacked one upon the other.

The wavelength of light emitted from the nitride-based semiconductor light-emitting element **300** depends on the mole fraction of In, x, in the $Ga_{1-x}In_xN$ semiconductor that is the semiconductor composition of the above-described well layers. A piezoelectric field would not be generated in the nitride semiconductor active layer **306** formed on the m-plane. Therefore, decrease of the luminous efficacy can be prevented even when the In mole fraction is increased.

The n-side electrode **309** has, for example, a multilayer structure of a Ti layer and a Pt layer (Ti/Pt). The p-side electrode **308** may generally cover the entire surface of the p-type nitride semiconductor layer **307**. The p-side electrode **308** has, for example, a multilayer structure of a Pd layer and a Pt layer (Pd/Pt).

The nitride-based semiconductor light-emitting element **300** is electrically connected to a wire **302** which is provided on a mounting base **301** via a bump **303**.

The substrate **304** of the nitride-based semiconductor light-emitting element **300** is enclosed by the principal surface **333**, the light extraction surface (rear surface) **331** that is generally parallel to the principal surface **333**, and the four lateral surfaces **332**. Light emitted by the nitride semiconductor active layer **306** mainly outgoes from the light extraction surface **331**. On the principal surface **333**, the semiconductor multilayer structure is provided. The principal surface **333**, the light extraction surface **331**, and the principal surface of the nitride semiconductor active layer **306** are generally parallel to one another.

In the present embodiment, a portion of light that is incident on the four lateral surfaces **332** may not be reflected at the respective lateral surfaces **332** but transmitted through the respective lateral surfaces **332**. As described herein, the four lateral surfaces **332** may be light extraction surfaces. The four lateral surfaces **332** are inclined with an angle greater than 90° with respect to the principal surface **333**. As a result, the area of the light extraction surface **331** is larger than the area of the principal surface **333** of the substrate **304**. An angle resulting from subtraction of 90° from this inclination is referred to as angle θ**1**. That is, an angle which is formed by the four lateral surfaces **332** with respect to the normal direction of the principal surface **333** is referred to as angle θ**1**.

The contour **351** of the light extraction surface **331** and the contour **352** of the principal surface **333** have square shapes in the top view. In the top view, the contour **351** and the contour **352** may be concentric, and the sides of the contour **351** and the sides of the contour **352** may be parallel to each other. With such an arrangement, all of the four angles θ**1** that are formed between the normal direction of the principal surface and the four lateral surfaces **332** are equal angles.

According to the present embodiment, the contour **352** is square, and therefore, the angle formed between the long axis direction of light which is converted to elliptical polarization at one of the lateral surfaces and the long axis direction of light which is converted to elliptical polarization at another lateral surface which is adjacent to the former lateral surface is a right angle. Thus, the polarization degree can be efficiently reduced. Further, the four lateral surfaces have generally equal areas, and therefore, the light distribution characteristics can be easily controlled.

The contours **351** and **352** may have similar shapes or may have different shapes. The contours **351** and **352** may have other quadrangular shapes or may have other polygonal shapes. The contours **351** and **352** may have a shape which includes a curve. The number of the lateral surfaces **332** may be three or may be five or more.

It is desirable that θ**1** is set to an angle which is equal to or greater than the critical angle θc that is determined by the refractive index of the substrate **304** and the refractive index of a portion surrounding the substrate **304**. Here, the refractive index of a portion surrounding the substrate **304** refers to the refractive index of a portion outside the lateral surfaces of the substrate. The portion outside the lateral surfaces of the substrate may be a resin, glass, air or vacuum. Specifically, $\theta c = \sin^{-1}(n2/n1)$ holds true where n**1** is the refractive index of the substrate **304** and n**2** is the refractive index of a portion surrounding the substrate **304**. Making θ**1** equal to or greater than the critical angle θc enables total reflection of light which is generated in the nitride semiconductor active layer **306** and which is then incident on the lateral surfaces **332**. Accordingly, the polarization degree can be further reduced. θ**1** may be equal to or greater than the critical angle Go and fall in the angle range of not less than 30° and less than 90°. When θ**1** is in this angle range, light which is reflected at the lateral surfaces **332** is extracted without undergoing total reflection at the light extraction surface **331**.

Where the absolute value of an angle formed between one of the sides of the contour **352** which is selected as an angular reference and the polarization direction **324** in the principal surface **333** of polarized light of the nitride-based semiconductor light-emitting element **300** is θ**2**, θ**2** (mod 180°) is an angle which does not include 0° or 90° (see FIG. **32**). Where the absolute value of an angle formed between a side which is adjacent to the side that is selected as an angular reference and the polarization direction **324** in the principal surface **333** of polarized light of the nitride-based semiconductor light-emitting element **300** is θ**2'**, θ**2'**=|90°−θ**2**| holds true because the contour **352** has a square shape.

Next, the principle of reducing the polarization in the configuration of the present embodiment is described with reference to FIGS. **7A** to **7C**. In FIGS. **7A** to **7C**, for the sake of simple illustration, the n-side electrode **309**, the p-side electrode **308**, the mounting base **301**, the wire **302**, and the bump **303** are omitted.

First, the shape of the nitride-based semiconductor light-emitting element **300** is defined. For the sake of simplicity, it is assumed that the contour of the light extraction surface **331** and the contour of the principal surface **333** are square. The refractive index of the substrate **304** is n**1**, and the refractive index of the surrounding portion is n**2**. The length of one side of the principal surface of the semiconductor multilayer structure is L**1**, the length of one side of the light extraction surface **331** is L**2**, and the distance between the light extraction surface **331** and the principal surface of the semiconductor multilayer structure is D. The four angles θ**1** that are formed between the normal direction of the principal surface of the semiconductor multilayer structure and the four lateral surfaces **332** are all equal. Here, the above assumptions lead to that the four light extraction surfaces are surfaces which have exactly equal shapes and exactly equal areas, although these surfaces are referred to as "lateral surface **332***a*", "lateral surface **332***b*", "lateral surface **332***c*", and "lateral surface **332***d*" such that they are distinguishable from one another. The lateral surface **332***a* and the lateral surface **332***c* face each other, and the lateral surface **332***b* and the lateral surface **332***d* face each other.

Next, the angles are defined. In FIG. **7**A, the angle θ**2** represents an angle formed by the polarization direction **324** in the principal surface of polarized light of the light emitted by the nitride semiconductor active layer **306** with respect to sides of the contour of the principal surface **333** which are in contact with the lateral surface **332***a* and the lateral surface **332***c*. The angle θ**2'** represents an angle formed by the polarization direction **324** in the principal surface of polarized light of the light emitted by the nitride semiconductor active layer **306** with respect to sides of the contour of the principal surface **333** which are in contact with the lateral surface **332***b* and the lateral surface **332***d*. Since the contour of the principal surface **333** is square, θ**2'**=90−θ**2** holds true. These angles θ**2** and θ**2'** are greater than 0° and smaller than 90° (angles which do not include 0° or 90°).

In FIG. **7**B, which shows the cross section taken along line X-X' of FIG. **7**A, the angle which is formed between the normal direction of the principal surface and the lateral surfaces **332** is referred to as θ**1**. Where the angle which is formed between the light extraction surface **331** and lateral surfaces **332** is θ**5**, θ**5**=90−θ**1** holds true. The length of one side of the light extraction surface **331** is determined by D, L**1**, and θ**5**. Now, in view of a case where light produced in the nitride semiconductor active layer **306** is incident on the lateral surfaces **332**, this light is referred to as "incident light **341**". Light which is reflected at the lateral surfaces **332** is referred to as "reflected light **342**". Light which is transmitted through the lateral surfaces **332** is referred to as "transmitted light **343**". The angle which is formed between the incident light **341** and the normal direction of the lateral surfaces **332** is referred to as θ**3**. The angle which is formed by the reflected light with respect to the normal direction of the light extraction surface **331** is referred to as θ**4**.

Hereinafter, a case where only one of the lateral surfaces **332** is considered, a case where the four lateral surfaces **332** are considered, and a case where all of the light extraction surfaces are considered are described in this order.

(Case where Only One of the Lateral Surfaces **332** is Considered)

Firstly, the polarization degree of light reflected by one of the lateral surfaces **332** is discussed.

The present embodiment utilizes a phenomenon that, when the incident light **341** is reflected by the lateral surface **332**, a phase difference occurs due to the Goos-Hanchen shift. When incident light includes a p-polarization component and an s-polarization component, Formula 1 and Formula 2 shown below are given:

$$\tan\left(\frac{\delta_p}{2}\right) = \frac{-\sqrt{\sin^2\theta_3 - (n_2/n_1)^2}}{(n_2/n_1)^2\cos\theta_3} \quad \text{(Formula 1)}$$

$$\tan\left(\frac{\delta_s}{2}\right) = \frac{-\sqrt{\sin^2\theta_3 - (n_2/n_1)^2}}{\cos\theta_3} \quad \text{(Formula 2)}$$

where δp is a shift of the phase which occurs at the time of reflection of the p-polarization and δs is a shift of the phase which occurs at the time of reflection of the s-polarization.

Further, Formula 3 shown below is given:

$$\tan\left(\frac{\delta}{2}\right) = \frac{\cos\theta_3\sqrt{\sin^2\theta_3 - (n_2/n_1)^2}}{\cos^2\theta_3} \quad \text{(Formula 3)}$$

where δ is the relative phase difference.

When the light is reflected, a phase difference occurs between the s-polarized light and the p-polarized light according to the ratio of the refractive indices at the interface. Thus, when it is configured such that the incident light **341** on the lateral surface **332** includes the p-polarization component and the s-polarization component, incident linearly-polarized light can be converted to elliptical polarization (or circular polarization), so that the polarization degree can be reduced.

In the case where the polarized light is assumed as linear polarization, the electric field component E of the light can be separated into a component E**1** that is parallel to sides which are in contact with the lateral surface **332***a* and the lateral surface **332***c* and a component E**2** that is parallel to sides which are in contact with the lateral surface **332***b* and the lateral surface **332***d*. Here, E**1** and E**2** are light which have equal phases. In this case, E**1** is the S-polarization component for the lateral surface **332***a* and the lateral surface **332***c*. On the other hand, E**2** is the S-polarization component for the lateral surface **332***b* and the lateral surface **332***d*. The phase of the S-polarization reflected light is in advance of that of the p-polarization reflected light.

FIG. **8**A shows the definition of the state of linear polarization the state of circular polarization, and the state of elliptical polarization. The trajectory of elliptically-polarized light is expressed as

$$\left(\frac{E_x}{A_{x0}}\right)^2 + \left(\frac{E_y}{A_{y0}}\right)^2 - 2\left(\frac{E_x}{A_{x0}}\right)\left(\frac{E_y}{A_{y0}}\right)\cos\delta = \sin^2\delta \quad \text{(Formula 4)}$$

or the following general expression, Formula 5:

$$\left(\frac{E_\xi}{a}\right)^2 + \left(\frac{E_\eta}{b}\right)^2 = 1 \quad \text{(Formula 5)}$$

Formula 4 is the definition for a case where a system of arbitrary x and y coordinates which are orthogonal to each other is used. A_{x0} is the electric field amplitude in the x direction, A_{y0} is the electric field amplitude in the y direction, E_x is the electric field in the x direction, E_y is the electric field in the y direction, and δ is the phase difference between the electric field amplitude in the x direction and the electric field amplitude in the y direction. Formula 5 is the definition for a case where the short axis direction and the long axis direction of an ellipse are set to the coordinate axes. When b>a holds true, $E\xi$ is the electric field in the short axis direction of the ellipse, $E\eta$ is the electric field in the long axis direction of the ellipse, a is the electric field amplitude in the short axis direction, and b is the electric field amplitude in the long axis direction. In that case, the oblateness of the ellipse is defined by polarization ellipticity χ as follows:

$$\tan\chi = \frac{b}{a} \quad \text{(Formula 6)}$$

The angle which is formed by the long axis direction of the ellipse with respect to the x direction is defined by the principal axis azimuth angle ϕ and expressed as follows:

$$\tan(2\phi)=\tan(2\alpha)\cdot\cos\delta \quad \text{(Formula 7)}$$

Here, α meets the following equation:

$$\tan\alpha=A_{y0}/A_{x0} \quad \text{(Formula 8)}$$

As seen from the above, the relative phase difference occurs between the s-polarized light and the p-polarized light according to the ratio of the refractive indices at the interface, and the linearly-polarized light is converted to the elliptical polarization.

Light emitted from the nitride semiconductor active layer **306** emits in various directions. Here, the angle range in which θ**3** can fall is discussed with reference to FIG. **7**C, which shows a cross-sectional view taken along line X-X' of FIG. **7**A. θ**3** is the smallest in the case of incident light A of FIG. **7**C, where light emitted from the nitride semiconductor active layer **306** travels in the plane direction of the nitride semiconductor active layer **306**. In this case, θ**3** is equal to θ**1**. θ**3** is the largest in the case of incident light B of FIG. **7**C, where light emitted from an end portion of the nitride semiconductor active layer **306** travels along the lateral surface **332**. In this case, θ**3** is 90°. Therefore, θ**3** falls in the range of not less than θ**1** and not more than 90°.

For utilizing reflection at the lateral surface **332**, a large portion of the light may be reflected at the lateral surface **332**. Since θ**3** falls in the range of not less than θ**1** and not more than 90°, substantially all of the incident light **341** is totally reflected at the lateral surface **332**, so long as θ**1** is equal to or greater than the critical angle θc. If θ**4**<θc holds true, light reflected at the lateral surface **332** can be extracted at the light extraction surface **331**. In view of the relationships of θ**4**=θ**5**−θ**3** and θ**5**=90−θ**1**, θ**4**=90−θ**1**−θ**3**<θc holds true. In view of the aforementioned conditions, θ**3** may fall in the range of not less than θ**1** and not more than 90°. When θ**3**=θ**1** holds true, θ**4** is the largest, and 90−2·θ**1**<θc holds true. The angle range of θc which satisfies this formula and the relationship of θ**1**>θc at the same time is not less than 30° and not more than 90°.

FIG. **9**A is a graph showing the relationship of the critical angle with respect to the refractive index n**2** where the refractive index of a gallium nitride, 2.5, is employed as the refractive index n**1**. As the refractive index n**2**, i.e., the refractive index of a portion surrounding the nitride-based semiconductor light-emitting element **300**, increases, the critical angle also increases. This means that light is more readily extracted from the nitride-based semiconductor light-emitting element **300** to the outside. As seen from FIG. **9**A, when the refractive index n**1** is 2.5, a value of the refractive index n**2** which satisfies the condition that the critical angle θc is not less than 30° is not less than 1.25. That is, the critical angle θc is not less than 30° when the value of n**2** is not less than a half of the value of n**1**.

FIG. **9**B shows incidence angles θ**3** on the lateral surface **332** on the horizontal axis and calculated values of the relative phase difference δ between the s-polarization and the p-polarization of the reflected light **342** on the vertical axis. The refractive index n**1** is 2.5, and the refractive index n**2** is varied from 1.0 to 1.8.

Only under the condition that the relative phase difference δ is 90°, the reflected light **342** on the lateral surface **332** is converted to circular polarization. Perfect circular polarization is realized when n**2** is in the range from 1.0 to 1.2. Actually, the angle range of θ**3** can be not less than θc and not more than 90°, and therefore, the reflected light **342** is converted to elliptical polarization.

FIG. **8**B shows calculation results of the relationship between the polarization ellipticity χ of the reflected light **342** and θ**2** in the case where θ**1** is equal to the critical angle θc. Here, θ**2** refers to the angle θ**2** that is formed between the polarization direction **324** in the principal surface of polarized light of the nitride-based semiconductor light-emitting element **300** and the contour of the light extraction surface **331** and the respective sides of the principal surface **333**. n**2** is varied from 1.2 to 1.8 with intervals of 0.1. The polarization ellipticity χ is the maximum when θ**2** is 45°, resulting in an upwardly convex curve. As the refractive index n**2** decreases, the polarization ellipticity χ increases.

FIG. **8**(*c*) shows calculation results of the relationship between the polarization degree of the reflected light **342** and θ**2** in the case where θ**1** is equal to the critical angle θc. n**2** is varied from 1.2 to 1.8 with intervals of 0.1. The polarization degree is the minimum when θ**2** is 45°, resulting in a downwardly convex curve. The refractive index n**2** decreases as the polarization degree decreases. As seen from FIG. **8**(*c*), θ**2** may be from 35° to 55°. θ**2** may be in the range from 40° to 50°. When θ**2** is in this range, the polarization degree can be further decreased.

It is proved from the above calculation results that the polarization degree can be reduced by converting the reflected light **342** to elliptical polarization by using a phase difference which occurs due to the Goos-Hanchen shift.

When θ**1** is equal to or greater than the critical angle θc as described above, almost all of light which is incident on the lateral surface **332** can be reflected. Note that, however, θ**1** may be smaller than the critical angle θc and may be in a range which will be described below.

FIG. **10**A is a graph showing the proportion (simulation result) of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from a light extraction surface **331**. In FIG. **10**A, the horizontal axis represents the angle θ**1**, and the vertical axis represents the proportion of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from a light extraction surface **331**. The results shown in FIG. **10**A were obtained on the assumption that the refractive index of GaN was 2.5, and four cases of the refractive index n**2** were 1.2, 1.4, 1.6, and 1.8.

FIG. **10**B is a graph where values are plotted at which the proportion of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from a light extraction surface **331** is 70% in the graph of FIG. **10**A. In the graph of FIG. **10**B, the horizontal axis represents the refractive index n**2**, and the vertical axis represents the values of the angle θ**1** at which the above-described proportion is 70%. As seen from FIG. **10**B, as the value of the refractive index n**2** increases, the value of the vertical axis decreases with a constant slope. The profile of FIG. **10**B is expressed as Formula 9 shown below:

$$\theta 1=51.0-21.5\times n2 \quad \text{(Formula 9)}$$

As seen from the above results, when θ**1** is greater than the value of Formula 9, the proportion of part of the light incident on the lateral surface **332** which is reflected at the lateral surface **332** and outgoing from a light extraction surface **331** can be not less than 70%.

(Case where Four Lateral Surfaces **332***a*, **332***b*, **332***c*, and **332***d* are Considered)

Next, the polarization degree for a case where all of the light reflected at the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d* are considered is discussed. Here, the discussion is provided with again reference to FIG. **7**A. In the discussion, the electric field component E of polarized light is separated into E**1** and E**2**. In this case, E**1** is the S-polarization component for the lateral surface **332***a* and the lateral surface **332***c*. On the other hand, E**2** is the S-polarization component for the lateral surface **332***b* and the lateral surface **332***d*. Here, assuming that the principal axis azimuth angle of light which is converted to elliptical polarization at the lateral surfaces **332** is θ**6**, the principal axis of the ellipse is inclined with respect to E**1** for the lateral surface **332***a* and the lateral surface **332***c*, and the principal axis of the ellipse is inclined with respect to E**2** for the lateral surface **332***b* and the lateral surface **332***d*. Here, E**1** and E**2** are inclined by 90°, and therefore, the principal axis of light which is converted to elliptical polarization at the lateral surface **332***a* and the lateral surface **332***c* and the principal axis of light which is converted to elliptical polarization at the lateral surface **332***b* and the lateral surface **332***d* are inclined by 90°. That is, light which is reflected at the lateral surfaces **332** and extracted from the light extraction surface **331** is superposition of elliptically-polarized light whose principal axes are inclined by 90°. Therefore, reflected light at the lateral surface **332***a* and the lateral surface **332***c* and reflected light at the lateral surface **332***b* and the lateral surface **332***d* are superposed such that the polarization degree is reduced. Thus, the polarization degree of overall light which is extracted from the nitride-based semiconductor light-emitting element **300** can be reduced.

FIG. **11** shows calculation results of the relationship between the polarization degree of the reflected light **342** and θ**2** in the case where the effects of the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d* are considered and θ**1** is equal to the critical angle θc. n**2** is varied from 1.2 to 1.8 with intervals of 0.1. It can be understood that the polarization degree can be greatly reduced as compared with FIG. **8**(*c*), because the reflected light at the lateral surface **332***a* and the lateral surface **332***c* and the reflected light at the lateral surface **332***b* and the lateral surface **332***d* function so as to reduce the polarization degree. θ**2** may be in the range from 25° to 65°. When θ**2** is in this range, the polarization degree of the reflected light can be reduced to a level which is not more than 0.2. More specifically, θ**2** may be in the range from 35° to 55°. When θ**2** is in this range, the polarization degree of the reflected light can be reduced to a level which is not more than 0.1. More specifically, θ**2** may be in the range from 40° to 50°. When θ**2** is in this range, the polarization degree of the reflected light can be reduced to a level which is not more than 0.05. When θ**2** is 45°, the polarization degree of light reflected at the lateral surfaces **332** can be generally 0 (zero). As the refractive index n**2** decreases, the polarization degree also decreases. However, it can be seen from the comparison with FIG. **8**C that the dependence of the polarization degree on n**2** is small.

It can be understood from the above that, in the embodiment, light is allowed to be reflected at the lateral surfaces **332** such that the light is converted to elliptical polarization, and elliptically-polarized light whose principal axes are inclined by 90° are synthesized, whereby the polarization degree of light emitted from the nitride-based semiconductor light-emitting element **300** can be greatly reduced.

(Case where all of the Light Extraction Surfaces are Considered)

Lastly, the polarization degree for a case where all of the light extraction surfaces are considered is discussed. That is, light outgoing from the light extraction surface **331** is considered in addition to the light reflected at the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d*.

Light which is emitted from the nitride semiconductor active layer **306** and directly extracted from the light extraction surface **331** to the outside maintains its polarization and impedes reduction of the polarization degree. The amount of light which is directly extracted from the light extraction surface **331** to the outside strongly depends on the critical angle θc and on the area ratio of the light extraction surface **331** to the lateral surfaces **332**. Here, the critical angle θc is determined by the refractive indices n**1** and n**2**. On the other hand, the area ratio is determined by the length of one side of the principal surface **333**, L**1**, the length of one side of the light extraction surface **331**, L**2**, and the distance between the light extraction surface **331** and the principal surface of the semiconductor multilayer structure, D.

Here, assuming that the angle θ**1** that is formed between the normal direction of the principal surface and the lateral surfaces **332** is θc and n**1** is 2.5 of a gallium nitride, L**2** is determined by L**1**, D, and θc, and θc is determined by n**2**. Therefore, it is not necessary to consider L**2**. This means that, if the refractive index n**2** of a material which overmolds the nitride-based semiconductor element is determined, the parameters that determine the contour of the nitride-based semiconductor element are D and L**1**.

Hereinafter, the discussion is carried on with n**2** and D/L**1**, which is the ratio of D to L**1**, as the parameters. FIG. **12**A shows how the proportion of light which is extracted from the light extraction surface **331** to the outside with its polarization being maintained depends on D/L**1** and n**2**. The calculation was carried out with n**2** being varied from 1.2 to 1.8 with intervals of 0.1. As D/L**1** increases, or as n**2** decreases, the proportion of light which is extracted from the light extraction surface **331** to the outside with its polarization being maintained decreases. As seen from FIG. **11**, it can be said that the polarization degree of reflected light at the lateral surfaces **332** has a small dependence on n**2**, but light which is directly extracted from the light extraction surface **331** depends on n**2**. D/L**1** may be not less than 0.1 or may be not less than 0.2.

Next, the area of the nitride semiconductor active layer **306** is discussed. According to the present embodiment, the length of one side of the principal surface **333**, L**1**, may be smaller than the length of one side of the light extraction surface **331**, L**2**. This means that the area of a portion in which the nitride semiconductor active layer **306** is provided is small relative to the area of the substrate **304**. This means that, when the nitride-based semiconductor light-emitting element shown in FIG. **3** and the nitride-based semiconductor light-emitting element of the present embodiment are compared with respect to an identical substrate area, the electric current density is higher in the configuration of the present embodiment. In other words, the above means that when the nitride-based semiconductor light-emitting element shown in FIG. **3** and the nitride-based semiconductor light-emitting element of the present embodiment are compared with respect to an identical electric current density, a larger substrate area is necessary in the configuration of the present embodiment.

On the other hand, comparing with a case where the principal surface of the nitride-based semiconductor light-emitting element is a polar plane (c-plane), the present embodiment can realize a configuration which is also advantageous in respect of the electric current density or the substrate area. This is because a nitride-based semiconductor light-emitting element whose principal surface is a non-polar plane or a semi-polar plane is characterized in that the efficiency is maintained even in the case of a high electric current density. FIG. **13** shows experimental results which illustrate the electric current density dependence of the external quantum efficiency (EQE) of a nitride-based semiconductor light-emitting element whose principal surface is an m-plane and a nitride-based semiconductor light-emitting element whose principal surface is a c-plane. The values of the EQE were normalized with the maximum value. These nitride-based semiconductor light-emitting elements were manufactured using a manufacturing method which will be described later. The configuration of the nitride-based semiconductor light-emitting elements is the same as that shown in FIG. **3**. θ**1** and θ**2** are 0°. In the nitride-based semiconductor light-emitting element manufactured on an m-plane GaN substrate, decrease of the EQE is small even in the case of a high electric current density. In view of the conditions which realize equal EQE in FIG. **13**, it can be seen that, in the nitride-based semiconductor light-emitting element manufactured on an m-plane GaN substrate, the electric current density can be increased to a level which is 4.2 times that of the nitride-based semiconductor light-emitting element which is manufactured on a c-plane GaN substrate. Here, the area occupation ratio of the nitride semiconductor active layer **306**, R, is defined as Formula 10. As for the area occupation ratio R of the nitride semiconductor active layer **306**, the area occupation ratio R=0.24, with which the electric current density is increased 4.2-fold, is an estimated value of the minimum. Thus, it means that, when R is not less than 0.24, a light-emitting element can be realized which is capable of high optical output as compared with a nitride-based semiconductor light-emitting element whose principal surface is a polar plane (c-plane).

$$R = \frac{L1^2}{L2^2} \qquad \text{(Formula 10)}$$

FIG. **12**B shows the relationship between n**2** and D/L**1** for respective values of the area occupation ratio R. When the area occupation ratio R is determined, the relationship between n**2** and D/L**1** is determined. For example, when R=0.24, D/L**1** may be set to a value which is not more than 0.5. More specifically, when the nitride-based semiconductor light-emitting element is overmolded with a material whose refractive index is generally from 1.4 to 1.5, such as a silicone resin, D/L**1** may be set to about 0.3.

The relationship between D/L**1** and the polarization degree in a case where θ**2** was varied from 5° to 45° with intervals of 5° was calculated with the refractive index n**2** being varied from 1.9 to 1.2 with intervals of 0.1 based on the above calculation results. The results of the calculation are shown in FIG. **14**A to FIG. **14**H. The broken line shown in the graphs represents a value of D/L**1** which leads to R=0.24. A region on the right side of the broken line represents a beneficial region in respect of the configuration. In FIG. **14**A to FIG. **14**H, the minimum value of the polarization degree is determined by light which is directly extracted from the light extraction surface **331** with its polarization being maintained. It is illustrated that the amount of the light which is directly extracted from the light extraction surface **331** with its polarization being maintained depends on D/L**1**, θ**2**, and n**2**.

FIG. **15** is a graph edited from the graphs of FIG. **14**A through FIG. **14**H, for the sake of clarity, for a case where R is not less than 0.24 and θ**1** is equal to or greater than the critical angle θc. FIG. **15** illustrates the ranges of n**2** and θ**2** which satisfy the following conditions: the polarization degree is not more than 0.30 (region A); the polarization degree is not more than 0.25 (region B); the polarization degree is not more than 0.20 (region C); the polarization degree is not more than 0.15 (region D); and the polarization degree is not more than 0.10 (region E). Here, the "region" includes the solid line and the entire area enclosed by the solid line. As seen from FIG. **15**, θ**2** may be a value which is as close to 45° as possible, and the value of n**2** may be as small as possible.

The calculation results which have been described in the previous sections are calculation results which are on the assumption that light emitted from the nitride semiconductor active layer **306** is complete polarization, i.e., calculation results for light whose polarization degree is 1. As seen from FIG. **4**, in an actual nitride-based semiconductor light-emitting element, the polarization degree of light emitted from the nitride semiconductor active layer **306** depends on the emission wavelength and has a value of about 0.3 to 0.8. That is, a value obtained by multiplying the value of the polarization degree of FIG. **15** by the polarization degree of light emitted from the nitride semiconductor active layer **306** is the polarization degree of the entire light-emitting element. That is, in a near-ultraviolet range where the emission wavelength is about from 400 nm to 410 nm, a polarization degree of not more than 0.1 can be realized in the region C of FIG. **15**. In a blue range where the emission wavelength is about from 440 nm to 460 nm, a polarization degree of not more than 0.1 can be realized in the region E of FIG. **15**.

Next, a manufacturing method of the present embodiment, i.e., Embodiment 1, is described with reference to FIG. **6**.

An n-type nitride semiconductor layer **305** is epitaxially grown using an MOCVD method on a substrate **304** which is made of n-type GaN with an M-plane principal surface. For example, the n-type nitride semiconductor layer **305** which is made of GaN and which has a thickness of about not less than 1 μm and not more than 3 μm is formed at a growth temperature of not less than 900° C. and not more than 1100° C., using silicon as the n-type impurity, while TMG ($Ga(CH_3)_3$) and NH_3 as the source materials are supplied.

Then, a nitride semiconductor active layer **306** is formed on the n-type nitride semiconductor layer **305**. The nitride semiconductor active layer **306** has a GaInN/GaN multi-quantum well (MQW) structure in which, for example, 15 nm thick $Ga_{1-x}In_xN$ well layers and 30 nm thick GaN barrier layers are alternately stacked one upon the other. In forming the $Ga_{1-x}In_xN$ well layers, the growth temperature may be decreased to 800° C. such that In can be taken in. The emission wavelength is selected according to the use for the nitride-based semiconductor light-emitting element **300**, and the In mole fraction x is determined according to the wavelength. When the wavelength is 450 nm (blue), the In mole fraction x is determined to be in the range of not less than 0.18 and not more than 0.2. When the wavelength is 520 nm (green), x is not less than 0.29 and not more than 0.31. When the wavelength is 630 nm (red), x is not less than 0.43 and not more than 0.44.

A p-type nitride semiconductor layer **307** is formed on the nitride semiconductor active layer **306**. For example, the p-type nitride semiconductor layer **307** which has a thickness of about not less than 50 nm and not more than 500 nm and which is made of p-type GaN is formed at a growth temperature of not less than 900° C. and not more than 1100° C., using Cp_2Mg (cyclopentadienyl magnesium) as the p-type impurity, while TMG and NH_3 as the source materials are supplied. Inside the p-type nitride semiconductor layer **307**, a p-AlGaN layer which has a thickness of about not less than 15 nm and not more than 30 nm may be included. Providing the p-AlGaN layer enables prevention of an overflow of electrons in operation.

Then, for the purpose of activating a p-GaN layer, a heat treatment is performed at a temperature of about not less than 800° C. and not more than 900° C. for about 20 minutes.

Then, dry etching is performed using a chlorine gas such that the p-type nitride semiconductor layer **307**, the nitride semiconductor active layer **306**, and the n-type nitride semiconductor layer **305** are partially removed to form a recessed portion **312**, whereby part of the n-type nitride semiconductor layer **305** is exposed.

Here, by controlling the conditions for the dry etching, an angle formed between a lateral surface **360** of the nitride semiconductor multilayer structure which is formed by a portion of the n-type nitride semiconductor layer **305**, the nitride semiconductor active layer **306**, and the p-type nitride semiconductor layer **307** and the normal direction of the principal surface can be controlled. For example, when such conditions that provide a high physical etching property are employed where the etching pressure is decreased and the ion extraction voltage is increased, a lateral surface which is generally perpendicular to the light extraction surface **311** can be formed. On the other hand, when such conditions that provide a high chemical etching property are employed where an ICP plasma source of high plasma density is used and the ion extraction voltage is low, a lateral surface which is inclined with respect to the normal direction of the light extraction surface **311** can be formed.

Then, an n-side electrode **309** is formed so as to be in contact with the exposed part of the n-type nitride semiconductor layer **305**. For example, Ti/Pt layers are formed as the n-side electrode **309**. Further, a p-side electrode **308** is formed so as to be in contact with the p-type nitride semiconductor layer **307**. For example, Pd/Pt layers are formed as the p-side electrode **308**. Thereafter, a heat treatment is performed such that the Ti/Pt layers and the n-type nitride semiconductor layer **305** are alloyed together, and the Pd/Pt layers and the p-type nitride semiconductor layer **307** are also alloyed together.

Thereafter, the substrate **304** is ground so as to be a thin film. In this process, the substrate **304** is ground such that the distance between the light extraction surface **331** and the principal surface of the semiconductor multilayer structure, D, has an intended value.

The thus-manufactured nitride-based semiconductor light-emitting element **300** is separated into small chips. By the separation process, θ**1** and θ**2** can be controlled. For the separation process, laser dicing, cleaving or blade dicing may be used.

FIGS. **16**(*a*) and **16**(*b*) illustrate a method for forming the lateral surfaces **332** by means of laser dicing. FIG. **16**(*a*) is a cross-sectional view. FIG. **16**(*b*) is a top view. As illustrated in the cross-sectional view of FIG. **16**(*a*), after the substrate **304** is attached to a dicing tape **371**, a laser light source **372** is placed obliquely with respect to the normal direction of the substrate **304** and is driven such that laser light **373** is incident obliquely with respect to the normal direction of the substrate **304**. Here, the angle which is formed between the laser light **373** and the normal direction of the substrate **304** is θ**1**. The substrate material is melted by the laser light **373**, whereby the substrate is separated into small chips. In this process, the lateral surfaces **332** are formed. The laser light may be provided so as to reach the dicing tape **371**. As illustrated in the top view of FIG. **16**(*b*), the scanning direction **374** of the laser light **373** is set so as to form an angle of θ**2** (θ**2'**) with respect to the polarization direction **324** in the principal surface of polarized light emitted from the nitride semiconductor active layer **306**. In the laser dicing, it is necessary to perform laser light scanning at least four times for formation of the four lateral surfaces **332**.

FIGS. **17**(*a*) and **17**(*b*) illustrate a method for forming the lateral surfaces **332** by means of blade dicing. FIG. **17**(*a*) is a cross-sectional view. FIG. **17**(*b*) is a top view. As illustrated in the cross-sectional view of FIG. **17**(*a*), the blade dicing employs a dicing blade **375** which has slopes at the edge. Here, the settings are determines such that the angles which are formed between the slope surfaces **376** at the edge of the dicing blade and the normal direction of the principal surface of the substrate **304** are el. After the substrate **304** is attached to a dicing tape **371**, dicing of the substrate **304** is carried out such that the shape of the slope surfaces **376** at the dicing blade edge is transferred to the substrate **304**, whereby the lateral surfaces **332** are formed. As illustrated in the top view of FIG. **17**(*b*), the scanning direction **377** of the blade dicing is set so as to form an angle of θ**2** (θ**2'**) with respect to the polarization direction **324** in the principal surface of polarized light emitted from the nitride semiconductor active layer **306**. In the blade dicing, the lateral surfaces **332** of adjoining nitride-based semiconductor light-emitting elements **300** are simultaneously formed. Therefore, the blade dicing is advantageous in that the number of times of the scanning is smaller than that of the laser dicing.

According to the present embodiment, the principal surface **333** and the light extraction surface (rear surface) **331** of the substrate **304** have square shapes. Therefore, in the process of separating the nitride-based semiconductor light-emitting elements **300** into small chips, the scanning direction of laser light or cutting with a dicing blade is maintained parallel, and the manufacturing process is easy.

FIGS. **18**A and **18**B show an example where the angles formed between the slope surfaces **376** at the dicing blade edge and the normal direction of the principal surface of the substrate **304** were set to 45°, and the blade dicing was carried out on the substrate **304** which had a thickness of 100 μm. In this process, the dicing was also performed on the dicing tape, together with the substrate **304**, to the depth of 100 μm. FIG. **18**(*a*) is a photographic image of the top surface, from which it is seen that the lateral surfaces **332** were formed. FIG. **18**B is a graph showing a cross-sectional profile taken along Y-Y' direction. It is seen that the angles formed between the lateral surfaces **332** and the normal direction of the principal surface were 45°, and that the slope surfaces **376** at the dicing blade edge were transferred to the substrate **304**.

The nitride-based semiconductor light-emitting element **300** that has been separated into a small chip as described above is mounted on the mounting base **301**. Here, a flip-chip structure is described with again reference to FIG. **6**.

On the mounting base **301**, the wire **302** has been formed in advance. As the base material of the mounting base, an insulating material such as alumina or AlN, a metal such as Al or Cu, a semiconductor such as Si or Ge, or a composite material thereof may be used. When the metal or semiconductor is used as the base material of the mounting base **301**, the surface of the mounting base **301** may be covered with an insulating film. The wire **302** may be arranged according to the electrode shape of the nitride-based semiconductor light-emitting element **300**. For the wire **302**, Cu, Au, Ag or Al may be used. The wire **302** may be arranged according to the electrode shape of the nitride-based semiconductor light-emitting element **300**. For the wire **302**, Cu, Au, Ag or Al may be used. These materials may be provided on the mounting base **301** by sputtering or plating.

A bump **303** is formed on the wire **302**. Au may be used for the bump. In forming the Au bump, a Au bump having a diameter of about not less than 50 μm and not more than 70 μm may be formed using a bump bonder. Alternatively, the Au bump may also be formed by Au plating. To the mounting base **301** on which the bump **303** has been formed in this way, the nitride-based semiconductor light-emitting element **300** is connected by ultrasonic bonding.

In this way, the semiconductor light-emitting device of the embodiment is completed.

FIG. **19**(*a*) is a top view schematically showing a nitride-based semiconductor light emitting device of Variation 1 of Embodiment 1. FIG. **19**(*b*) is a cross-sectional view taken along line X-X' of FIG. **19**(*a*). FIG. **19**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **19**(*a*). Detailed descriptions of disclosures which are common among FIG. **6** and FIG. **19** are herein omitted. In the previously-described example of the first embodiment, the four angles θ**1** which are formed between the normal direction of the principal surface and the four lateral surfaces **332** are equal to one another, whereas the angles θ**1** are all different in Variation 1 of Embodiment 1. For example, in the case where the center of the square formed by the contour **351** of the light extraction surface **331** and the center of the square formed by the contour **352** of the principal surface **333** are not coincident with each other, the angles θ**1** are different from one another. Due to the problem of machining accuracy, it is difficult to make the four angles θ**1** exactly equal to one another. However, even when the angles θ**1** are different from one another, the previously-described polarization reducing effect is achieved likewise. In this variation also, when the four angles θ**1** (θ**1***a*, θ**1***b*, θ**1***c*, and θ**1***d*) satisfy Formula 9, the proportion of part of the light incident on the lateral surfaces **332** which is reflected at the lateral surfaces **332** and outgoing from the light extraction surface **331** can be not less than 70%. When the four angles θ**1** are greater than the critical angle θc, the light can be efficiently reflected at each of the lateral surfaces. Note that, however, the four angles θ**1** do not necessarily meet these conditions, but at least one of the angles θ**1** may meet these conditions.

FIG. **20**(*a*) is a top view schematically showing a nitride semiconductor light-emitting device of Variation 2 of Embodiment 1. FIG. **20**(*b*) is a cross-sectional view taken along line X-X' of FIG. **20**(*a*). FIG. **20**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **20**(*a*). Detailed descriptions of disclosures which are common among FIGS. **6** and FIG. **20** are herein omitted. In the previously-described example of the first embodiment shown in FIG. **6**, the lateral surfaces **360** of the nitride semiconductor multilayer structure which is formed by the n-type nitride semiconductor layer **305**, the nitride semiconductor active layer **306**, and the p-type nitride semiconductor layer **307** are parallel to the normal direction of the principal surface. However, as shown in FIG. **20**, the lateral surfaces **360** of the nitride semiconductor multilayer structure which is formed by the n-type nitride semiconductor layer **305**, the nitride semiconductor active layer **306**, and the p-type nitride semiconductor layer **307** may be inclined by an angle of θ**1'** with respect to the normal direction of the principal surface. In this case, θ**1'** may be greater than the value of Formula 9 or may be greater than the critical angle θc. With such an arrangement, light which is emitted from the nitride semiconductor active layer **306** and outgoing in a direction of a plane on which the semiconductor multilayer structure is formed can be efficiently totally reflected at the lateral surfaces **360** of the nitride semiconductor multilayer structure.

FIG. **21**(*a*) is a top view schematically showing a nitride-based semiconductor light-emitting device of Variation 3 of Embodiment 1. FIG. **21**(*b*) is a cross-sectional view taken along line X-X' of FIG. **21**(*a*). FIG. **21**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **21**(*a*). Detailed descriptions of disclosures which are common among FIG. **6** and FIG. **21** are herein omitted. The difference from FIG. **6** resides in that the nitride-based semiconductor light-emitting element is covered with an overmold portion **314**. Examples of the material of the overmold portion **314** are epoxy, silicone or glass. The value of n**2** can be controlled by appropriately selecting the material of the overmold portion **314**. Also, by enclosing the nitride-based semiconductor light-emitting element having the overmold portion **314**, light extraction is improved, and the emission power can be increased. Further, permeation of moisture and gas can be prevented, and accordingly, the reliability improves. When silicone is used as the material of the overmold portion **314** for example, the value of n**2** can be controlled to a value which is not less than 1.40 and not more than 1.54. When an epoxy resin is used as the material of the overmold portion **314**, for example, the value of n**2** can be controlled to a value which is not less than 1.47 and not more than 1.60. These materials can be selected from thermosetting materials and UV-curable materials.

Embodiment 2

The second embodiment is described with reference to FIG. **22**. FIG. **22**(*b*) is a cross-sectional view taken along line X-X' of FIG. **22**(*a*). FIG. **22**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **22**(*a*). Detailed descriptions of disclosures which are common among FIG. **6** and FIG. **22** are herein omitted. The difference from Embodiment 1 resides in that the contour **351** of the light extraction surface **331** and the contour **352** of the principal surface **333** have rectangular shapes in the top view. In the top view, the contour **351** and the contour **352** may be concentric, and the sides of the contour **351** and the sides of the contour **352** may be parallel to each other. The rectangular contours improve the flexibility of the electrode layout.

When the contour **351** and the contour **352** have rectangular shapes, polarized light emitted from the nitride semiconductor active layer **306** is also reflected at the lateral surfaces **332** so as to be converted to elliptical polarization. Further, elliptically-polarized light whose principal axes are inclined by 90° are synthesized, whereby the polarization degree of light outgoing from the nitride-based semiconductor light-emitting element **300** can be reduced.

Where the absolute value of an angle formed between one of the sides of the contour **351** which is selected as an angular reference and the polarization direction **324** in the principal surface of polarized light of the nitride-based semiconductor light-emitting element **300** is θ**2**, θ**2** (mod 180°) is inclined by an angle which does not include 0° or 90°. Where the absolute value of an angle formed between a side which is in contact with the angular reference side and the polarization direction **324** in the principal surface of polarized light of the nitride-based semiconductor light-emitting element **300** is θ**2'**, θ**2'**=|90°−θ**2**| holds true because the contour **351** is rectangular.

As is in Embodiment 1, θ**2** may be in the range from 25° to 65°. When θ**2** is in this range, the polarization degree of reflected light can be reduced to a level which is not more than 0.2. More specifically, θ**2** may be in the range from 35° to 55°.

When $\theta 2$ is in this range, the polarization degree of reflected light can be reduced to a level which is not more than 0.1. When $\theta 2$ is 45°, the polarization degree of light reflected at the lateral surfaces **332** is the minimum.

As is in Embodiment 1, $\theta 1$ may be greater than a value which satisfies Formula 9 or may be equal to or greater than the critical angle θc, which is determined by **n1** and **n2**. Light can be efficiently reflected at the lateral surfaces **332**.

In Embodiment 2, it is desirable that the rectangular shapes and $\theta 1$ are set such that the areas of the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d* are as equal as possible.

The same manufacturing method as that of Embodiment 1 can also be employed herein.

Embodiment 3

The third embodiment is described with reference to FIG. **23**. FIG. **23**(*b*) is a cross-sectional view taken along line X-X' of FIG. **23**(*a*). FIG. **23**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **23**(*a*). Detailed descriptions of disclosures which are common among FIG. **6** and FIG. **23** are herein omitted. The difference from Embodiment 1 resides in that the contour **351** of the light extraction surface **331** and the contour **352** of the principal surface **333** have parallelogrammatic shapes in the top view. In the top view, the contour **351** and the contour **352** may be concentric, and the sides of the contour **351** and the sides of the contour **352** may be parallel to each other. The contour **351** and the contour **352** may have similar shapes. The parallelogrammatic contours improve the flexibility of the electrode layout.

Where the absolute value of an angle formed between one of the sides of the contour **351** which is selected as an angular reference and the polarization direction **324** in the principal surface of polarized light of the nitride-based semiconductor light-emitting element **300** is $\theta 2$, $\theta 2$ (mod 180°) is inclined by an angle which does not include 0° or 90°. Where the absolute value of an angle formed between a side which is in contact with the angular reference side and the polarization direction **324** in the principal surface of polarized light of the nitride-based semiconductor light-emitting element **300** is $\theta 2'$, if $\theta 6=\theta 2+\theta 2'$ holds true, $\theta 6$ is an interior angle of the parallelogram, and $\theta 6$ has a value which is greater than 0° and smaller than 180°.

When the contour **351** and the contour **352** have parallelogrammatic shapes, polarized light emitted from the nitride semiconductor active layer **306** is also reflected at the lateral surfaces **332** so as to be converted to elliptical polarization. Further, elliptically-polarized light whose principal axes are inclined by $\theta 6$ are synthesized, whereby the polarization degree of light outgoing from the nitride-based semiconductor light-emitting element **300** can be reduced.

$\theta 2$ and $\theta 2'$ may be in the range from 25° to 65°. When $\theta 2$ and $\theta 2'$ are in this range, the polarization degree of reflected light can be reduced to a level which is not more than 0.2. More specifically, $\theta 2$ and $\theta 2'$ may be in the range from 35° to 55°. When $\theta 2$ and $\theta 2'$ are in this range, the polarization degree of reflected light can be reduced to a level which is not more than 0.1. Particularly when $\theta 2=\theta 2'=\theta 6/2$ holds true, the polarization degree of light reflected at the lateral surfaces **332** is the minimum.

In view of the relationships of $\theta 6=\theta 2+\theta 2'$ and $\theta 2=\theta 2'$, $\theta 6$ may be in the range from 50° to 130° or may be in the range from 70° to 110°.

As is in Embodiment 1, $\theta 1$ may be greater than a value which satisfies Formula 9 or may be equal to or greater than the critical angle θc, which is determined by **n1** and **n2**. Light can be efficiently reflected at the lateral surfaces **332**.

In Embodiment 3, it is desirable that the parallelogrammatic shapes and $\theta 1$ are set such that the areas of the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d* are as equal as possible.

FIG. **24**(*a*) is a top view schematically showing a nitride-based semiconductor light-emitting device of Variation 1 of Embodiment 3. FIG. **24**(*b*) is a cross-sectional view taken along line X-X' of FIG. **24**(*a*). FIG. **24**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **24**(*a*). Detailed descriptions of disclosures which are common among FIG. **23** and FIG. **24** are herein omitted. In Variation 1 of Embodiment 3, the contour **351** of the light extraction surface **331** and the contour **352** of the principal surface **333** have rhombic shapes in the top view. The rhombus is a particular case of the parallelogram. All sides of the rhombus have the same length, and therefore, the areas of the four lateral surfaces **332***a*, **332***b*, **332***c*, and **332***d* can readily be equalized. That is, the amounts of light reflected at the respective lateral surfaces can readily be equalized. Thus, in synthesizing elliptically-polarized light whose principal axes are inclined by $\theta 6$, the polarization degree can be efficiently reduced.

The same manufacturing method as that of Embodiment 1 can also be employed herein for manufacture.

Embodiment 4

The fourth embodiment is described with reference to FIGS. **25**(*a*) to **25**(*f*). FIG. **25**(*b*) is a cross-sectional view taken along line X-X' of FIG. **25**(*a*). FIG. **25**(*c*) is a cross-sectional view taken along line Y-Y' of FIG. **25**(*a*). Detailed descriptions of disclosures which are common among FIG. **6** and FIG. **25** are herein omitted. The difference from Embodiment 1 resides in that the light extraction surface **331** has a plurality of recesses and elevations **334**. In the present embodiment, the surface that has the recesses and elevations **334** can be called "patterned surface".

One of the features of the present embodiment is that light is reflected at the lateral surfaces **332** so as to be converted to elliptical polarization, and further, elliptically-polarized light whose principal axes are inclined by 90° are synthesized, whereby the polarization degree of light outgoing from the nitride-based semiconductor light-emitting element **300** can be greatly reduced. Another one of the features is that the polarization degree of light which is directly extracted from the light extraction surface **331** can be reduced using the recesses and elevations formed in the light extraction surface **331**. With these features, the polarization degree of light extracted to the outside of the nitride-based semiconductor light-emitting element can be made close to generally 0 (zero).

In the present embodiment, elevated portions which have a rectangular cross-sectional shape may be provided in a striped pattern across the light extraction surface **331** as shown in FIG. **25**(*b*). More specifically, elevated portions which have a cross-sectional shape defined by a triangle or a curve line may be provided in a striped pattern across the light extraction surface **331** as shown in FIGS. **25**(*d*) and **25**(*e*). The period of the plurality of elevated portions may be not less than 300 nm and not more than 8 μm. This is because when the period of the elevated portions is less than 300 nm, light is less likely to be affected by the recesses and elevations **334**, and when the period of the elevated portions is more than 8 μm, the number of elevated portions formed across the light extraction surface **331** is small. In the top view, where the absolute value of an angle which is formed between the extending direction of the stripes and the polarization direction of polarized light is $\theta 7$, $\theta 7$ (mod 180°) may be not less than 5° and not more than 175°. More specifically, θ7 (mod 180°) may be not less than 30° and not more than 150°. With this angular range, the polarization can be reduced more effectively.

Another example of the plurality of recesses and elevations may be a configuration in which a plurality of elevated portions are two-dimensionally arranged as shown in FIG. **25**(*f*). The shape of these two-dimensionally arranged elevated portions may be a conical shape or a hemispherical shape. These two-dimensionally arranged elevated portions may not be arranged with equal intervals.

To examine the effect on the polarization degree of the plurality of recesses and elevations **334** formed in a striped pattern across the light extraction surface **331**, a light-emitting element shown in FIG. **26** was manufactured. The lateral surfaces **332** of the nitride-based semiconductor light-emitting element **300** were formed parallel to the c-plane and the a-plane of the nitride semiconductor crystal. The size of the nitride-based semiconductor light-emitting element **300** was a square of 300 μm. By forming the lateral surfaces **332** parallel to the c-plane and the a-plane in this way, the effect of the lateral surfaces **332** on the polarization degree was reduced, and only the effect of the recesses and elevations **334** was evaluated. The cross-sectional shape of the recesses and elevations in a striped pattern was approximate to an isosceles triangle. The interval of the elevations was 8 μm, and the height of the elevations was 2.5 μm. Measurement results of the normalized polarization degree with the absolute value of an angle which is formed between the extending direction of the stripes and the electric field direction of polarized light (the a-axis direction of the nitride semiconductor crystal), θ7, being varied to be 0°, 5°, 30°, 45°, and 90° are shown in FIG. **27**. The normalized polarization degree refers to a value normalized on the assumption that the value obtained when θ7 is 0° is 1.0. The normalized polarization degree is the minimum when θ7 is 45°. As seen from the measurement results shown in FIG. **27**, the range of θ7 may be from 5° to 90°. More specifically, the range of θ7 may be from 30° to 90°. θ7 may be 45°.

To examine the effect on the polarization degree of the plurality of recesses and elevations **334** formed across the light extraction surface **331**, a light-emitting element shown in FIG. **28** was manufactured. The lateral surfaces **332** of the nitride-based semiconductor light-emitting element **300** were formed parallel to the c-plane and the a-plane of the nitride semiconductor crystal. The size of the nitride-based semiconductor light-emitting element **300** was a square of 300 μm. By forming the lateral surfaces **332** parallel to the c-plane and the a-plane in this way, the effect of the lateral surfaces **332** on the polarization degree was reduced, and only the effect of the recesses and elevations **334** was evaluated. The shape of the elevated portions was approximate to a hemisphere. The height of the elevated portions was 5 μm. The base of the elevated portions had a circular shape having the diameter of 10 μm. The elevated portions were in a lattice arrangement having intervals of 20 μm.

FIG. **29** shows measurement results as to the polarization degree reducing effect in the case where the light extraction surface has recesses and elevations. Here, measured values are shown in the same graph together with the relationship between the emission wavelength and the polarization degree of the nitride-based semiconductor light-emitting element including an active layer formed on the m-plane which has previously been illustrated in FIG. **4**. That is, it can be seen that providing recesses and elevations across the light extraction surface **331** enables reduction of the polarization degree to generally a half.

FIG. **30** is a graph edited from the results of FIG. **29** and the results of FIG. **15**, showing appropriate ranges of and n**2** in Embodiment 4 for a case where the area occupation ratio R is not less than 0.24 and θ**1** is equal to or greater than the critical angle θc. FIG. **30** illustrates the ranges of n**2** and θ**2** which satisfy the following conditions: the polarization degree is not more than 0.15 (region A); the polarization degree is not more than 0.125 (region B); the polarization degree is not more than 0.1 (region C); the polarization degree is not more than 0.075 (region D); and the polarization degree is not more than 0.05 (region E). Here, the "region" includes the solid line and the entire area enclosed by the solid line. As seen from FIG. **30**, θ**2** may be a value which is close to 45°, and the value of n**2** may be as small as possible.

As seen from the above, providing a polarization degree reducing structure across the light extraction surface **331** enables further reduction of the polarization degree than Embodiment 1.

Next, a manufacturing method of Embodiment 4 is described. The manufacturing method of Embodiment 4 is the same as that of Embodiment 1 except for the method for forming the recesses and elevations **334**. Thus, herein, only the method for forming the recesses and elevations **334** is described.

A photoresist is applied over a surface of the substrate **304** in which recesses and elevations are to be formed, and resist patterning is performed using a contact exposure apparatus. Then, recesses and elevations are formed by dry etching with a chlorine gas using the photoresist as a mask. In this process, the conditions are made such that the photoresist is etched away concurrently, whereby the cross-sectional shape of the recesses and elevations in a striped pattern can be configured to have a shape which is approximate to an isosceles triangle. By making the dry etching conditions so as to achieve high chemical reactivity, elevated portions which have a hemispherical cross section as shown in FIG. **25** can be formed.

FIG. **31** is a schematic diagram showing an example of a white light source which includes the nitride-based semiconductor light-emitting element **300** of the embodiment. The light source shown in FIG. **31** includes the nitride-based semiconductor light-emitting element **300** that has the structure shown in FIG. **6** and a resin layer **400** in which a phosphor such as YAG (Yttrium Aluminum Garnet) is dispersed to change the wavelength of the light emitted from the nitride-based semiconductor light-emitting element **300** into a longer one. The nitride-based semiconductor light-emitting element **300** is mounted on a supporting member **410** on which a wiring pattern has been formed. A reflective member **420** is arranged on the supporting member **410** so as to surround the nitride-based semiconductor light-emitting element **300**. The resin layer **400** has been formed so as to cover the nitride-based semiconductor light-emitting element **300**.

In the embodiments described above, the p-type semiconductor region that is in contact with the p-side electrode **308** is supposed to be made of GaN or AlGaN. However, the p-type semiconductor region may be a layer including In, such as an InGaN layer, for example. In that case, the contact layer that is in contact with the p-side electrode **308** may be made of "$In_{0.2}Ga_{0.8}N$" in which the In mole fraction is 0.2, for example. If In is included in GaN, the bandgap of Al_aGa_bN (where a+b=1, and a≥0 and >0) can be smaller than that of GaN, and therefore, the contact resistance can be reduced as a result. Consequently, the p-type semiconductor region that is in contact with the p-side electrode **308** may be made of an $Al_xIn_yGa_zN$ semiconductor (where x+y+z=1, x≥0, y≥0 and z≥0).

According to the embodiments disclosed in the present application, the polarization degree of extracted light is reduced. Thus, the embodiments are applicable to decorative illumination and lighting devices.

While the present invention has been described with respect to preferred embodiments thereof, it will be apparent to those skilled in the art that the disclosed invention may be modified in numerous ways and may assume many embodiments other than those specifically described above. Accordingly, it is intended by the appended claims to cover all modifications of the invention that fall within the true spirit and scope of the invention.

What is claimed is:

1. A nitride-based semiconductor light-emitting element comprising:

a substrate which has a principal surface, a rear surface that is a light extraction surface, and a plurality of lateral surfaces; and

a nitride semiconductor multilayer structure formed on the principal surface of the substrate, wherein

the nitride semiconductor multilayer structure includes an active layer which emits polarized light,

the active layer has a principal surface of an m-plane;

angle θ is greater than 90°, and

angle $\theta\mathbf{2}$ (mod 180°) is an angle which does not include 0° or 90°,

where the angle θ is an angle which is formed by at least one of the plurality of lateral surfaces of the substrate with respect to the principal surface of the substrate, and

the angle $\theta\mathbf{2}$ is an absolute value of an angle which is formed by an intersecting line of at least one of the plurality of lateral surfaces of the substrate and the principal surface of the substrate with respect to a [11-20] direction.

2. The nitride-based semiconductor light-emitting element of claim **1**, wherein the substrate is an off-cut substrate of not more than 5°.

3. The nitride-based semiconductor light-emitting element of claim **1**, wherein a value of $(\theta-90°)$ is not less than a value of the angle $\theta\mathbf{1}$ which satisfies Formula 9:

$$\theta 1=51.0-21.5\times n2 \qquad \text{(Formula 9)},$$

where n**2** is a refractive index of a medium which is in contact with the plurality of lateral surfaces of the substrate.

4. The nitride-based semiconductor light-emitting element of claim **3**, wherein the value of $(\theta-90°)$ is greater than critical angle θc which is determined by refractive indices n**1** and n**2**, where n**1** is a refractive index for light of the substrate.

5. The nitride-based semiconductor light-emitting element of claim **1**, wherein planar shapes of the principal and rear surfaces of the substrate are a quadrangular shape, and the plurality of lateral surfaces are four lateral surfaces.

6. The nitride-based semiconductor light-emitting element of claim **5**, wherein planar shapes of the principal and rear surfaces of the substrate are a parallelogrammatic shape.

7. The nitride-based semiconductor light-emitting element of claim **5**, wherein planar shapes of the principal and rear surfaces of the substrate are a square shape.

8. The nitride-based semiconductor light-emitting element of claim **5**, wherein a planar shape of the principal surface and the rear surface of the substrate is a rectangular shape.

9. The nitride-based semiconductor light-emitting element of claim **5**, wherein planar shapes of the principal and rear surfaces of the substrate are a rhombic shape.

10. The nitride-based semiconductor light-emitting element of claim **1**, wherein the angle $\theta\mathbf{2}$ (mod 90°) is not less than 25° and not more than 65°.

11. The nitride-based semiconductor light-emitting element of claim **1**, wherein the angle $\theta\mathbf{2}$ (mod 90°) is not less than 35° and not more than 55°.

12. The nitride-based semiconductor light-emitting element of claim **1**, wherein the angle $\theta\mathbf{2}$ (mod 90°) is not less than 40° and not more than 50°.

13. The nitride-based semiconductor light-emitting element of claim **1**, wherein the rear surface of the substrate has a plurality of elevated portions.

14. The nitride-based semiconductor light-emitting element of claim **13**, wherein the elevated portions have a conical shape or a hemispherical shape and are two-dimensionally arranged across the rear surface of the substrate.

15. The nitride-based semiconductor light-emitting element of claim **13**, wherein

the elevated portions have a striped shape, and

γ (mod 180°) is not less than 5° and not more than 175° where γ is an absolute value of an angle which is formed between an extending direction of the striped shape and a polarization direction of the polarized light.

16. The nitride-based semiconductor light-emitting element of claim **15**, wherein γ (mod 180°) is not less than 30° and not more than 150°.

17. The nitride-based semiconductor light-emitting element of claim **1**, wherein

$\sigma 1$ (mod 180°) is not less than 85° and not more than 95° where $\sigma 1$ is an absolute value of an angle formed between a polarization direction of the polarized light and a normal line of the principal surface of the substrate, and

$\sigma 2$ (mod 180°) is not less than 85° and not more than 95° where $\sigma 2$ is an absolute value of an angle formed between the polarization direction of the polarized light and a normal line of the rear surface of the substrate.

18. A light source, comprising the nitride-based semiconductor light-emitting element as set forth in claim **1** and a wavelength converter including a phosphor that converts at least a wavelength of light emitted from the rear surface of the substrate.

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